Party Submission of

TALGO, INCORPORATED

1000 Second Avenue, Suite 1950
Seattle, Washington 98104

BEFORE THE NATIONAL TRANSPORTATION SAFETY BAORD

NTSB Accident Number: RRD-18MR001

December 18, 2017 Class: Major

Proposed findings in relation to the behavior of the railroad rolling stock involved and recommendations for improved safety in connection with the derailment of Amtrak Train 501, DuPont, Washington, Dec. 18, 2017

J.D. Coran,
Director, Product Development & Compliance
Talgo Incorporated, Seattle

Collaboration from:
J.A. Marcos
Manager, Maintenance Engineering
Patentes Talgo S.L.U., Madrid

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0 EXECUTIVE SUMMARY

On the morning of December 18, 2017, Amtrak train 501, consisting of the 12-unit Talgo *Mt. Adams* passenger train set, led by a Siemens locomotive and trailed by a GE locomotive, departed Seattle King Street station for Portland. This train was to be the first regularly scheduled *Cascades* train to use the newly rebuilt "Point Defiance Bypass" between Tacoma and Nisqually, Washington.

The train entered curve 19A-1, an 8-degree left hand curve at mile post 19.8 of the Lakewood Subdivision in DuPont, Pierce County, Washington, at 78 mph. The maximum speed allowed on this curve is 30 mph. As a result of its excessive speed, the locomotive derailed to the high side of the curve. The first five Talgo units followed the locomotive. All but one[1] of the Talgo units remained attached, upright and in line until they had all came to a stop about 517 feet after derailing.

The sixth Talgo unit, accessible coach 7504, was initially part of this first group, following the others off the high side of the curve; however, the car at its rear, coach 7424, initially remained on the track, causing the 7504 to rotate (clockwise as seen from above) until it was at about a right angle to its direction of travel. It was while it was in this orientation, traveling sideways, that it struck the concrete wall retaining the west side of the "bridge dump" (fill) behind the north abutment of bridge 19.90 over the southbound lanes of I-5. It was in this car that the three fatalities occurred.

As the front end of 7504 was already derailed to the high (right) side of the curve, the rotation caused its rear end to move towards the low (left) side. While this rotation quickly caused the car to break its connections, both ahead and behind, by the time the rear connection broke the car connected there, 7424, was already headed off the track to the left, taking the rest of the train in that direction and falling down the slope onto I-5 below.

Like the preceding two cars, the next two rotated in opposite directions, stacking up against each other, derailed but still supported by the rails and at near right angles to them. The last three Talgo cars[2] remained connected to each other and more or less inline, but derailed to the low (left) side of the curve. The lead car in that string, 7421, fell partially down the slope to the highway, but was stopped by landing on top of 7424, which was already lying there, upside down. As if all of the above was not enough, 7424 was hit by an 18-wheeler southbound on I-5 just after 7421 had landed on top of it.

These events produced forces far different from and in excess of any for which any railroad passenger equipment is designed. The collision with the retaining wall virtually destroyed the left side of car 7504, compromising the occupied space in that car. In all other cars, survival space was remarkably intact and no one in them was killed.

Talgo's investigation and analysis of the facts concluded that the equipment behaved very well under the extreme forces to which it was subjected. Its inherent safety features may have reduced the number of fatalities and injuries that would have occurred on a train made up of conventional North American passenger cars. The most relevant factors affecting this result are Talgo's light weight, end strength and overturning resistance. Additional factors are its low center of gravity and the method used to achieve radial axle positioning. All these design features and the performance of the Talgo equipment and components are examined in Section 2 of this report, with special

[1] The exception was the power car, which was directly behind the locomotive and maintained its alignment for almost all of the more than 500 feet the first portion of the train travelled after derailing, turning sideways and rolling onto one side only about 60 feet short.

[2] Also connected to this group and remaining so was GE locomotive, Amtrak 181, which was bringing up the rear of the train. It remained coupled to the last Talgo car and was the only vehicle on the train to remain entirely on the rails.

attention to cars C3 7504 and C4 7424.

In Section 3 we have benchmarked how different equipment and their components have behaved in accidents under some comparable conditions. Talgo's review of these accidents provided the basis for its conclusion that the Talgo equipment performed better than conventional equipment would have.

While, as we have explained in Section 4, we are convinced the equipment performed very well under the circumstances, our participation in the investigation of this accident (including the review of comparable accidents) has provided the opportunity to consider how the performance of Talgo equipment could be further improved. In Section 5 we have provided several suggestions for enhancements that have resulted from this opportunity.

In conclusion, we believe it is clear that the behavior of the Talgo equipment was far better than what would have been expected of conventional equipment in similar circumstances. The distributed energy absorption of the Talgo equipment combined with its light weight (which reduces the amount of kinetic energy that must be absorbed to bring the train to a stop) reduces the acceleration experienced by passengers and crew (and thus "secondary impact velocity" injuries). As demonstrated by the first group of cars at DuPont, the high degree of stability of Talgo equipment under heavy buff loading is much more likely to keep the equipment connected, upright and in line.

1 FACTUAL INFORMATION

1.1 ACCIDENT SYNOPSIS

On December 18, 2017, Amtrak train 501, consisting of the Talgo *Mt. Adams*, an articulated passenger train set led by a Siemens locomotive and trailed by a GE locomotive, departed Seattle King Street station for Portland at about 6:00 AM. This train was to be the first regularly scheduled Cascades train to use the newly rebuilt “Point Defiance Bypass” between Tacoma and Nisqually, Washington.

This report is limited to a description of the configuration, behavior and features of the Talgo designed equipment, the twelve-unit[3] articulated *Mt. Adams* trainset. Reference to the locomotives is made only to the extent it had an effect on the Talgo equipment.

Figure 1 below provides a schematic of the arrangement of the units (locomotives and Talgo cars) and rolling assemblies (trucks) at the time of the accident.

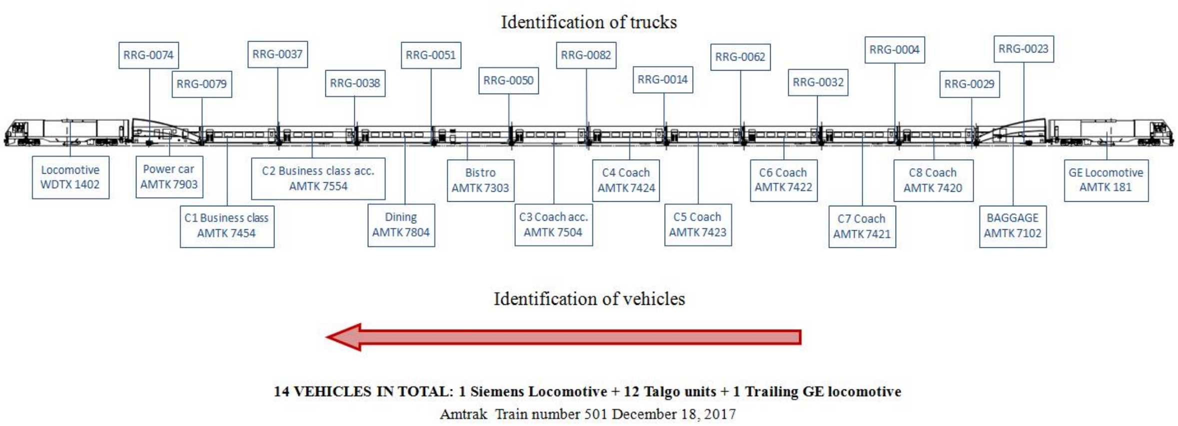


Figure 1 Train 501 configuration leaving Seattle (The arrow indicates direction of travel)

Entering 8 degree (717 foot radius) curve 19A-1 at MP (mile post) 19.8 of the Lakewood Subdivision in DuPont, Pierce County, Washington, at 78 mph the locomotive derailed to the high side of curve and then turned over, pulling the rest of the train with it. The maximum speed in this curve is 30 mph.

1.2 DERAILMENT SEQUENCE

1.2.1 *Talgo suspension*

To provide a better understanding of the sequence of the derailment, Figures 2 and 3 show the basic components of the Talgo suspension. There will be references to these components throughout this document.

[3] In this report the terms “unit” and “car” are used interchangeably. “Unit” is, however, more accurate because it refers to a rail vehicle segment between wheel assemblies, as opposed to a standard car, equipped with two underfloor trucks and thus able to run without the need of a connection to another segment. In that sense, the Talgo train set is one (articulated) “car”.

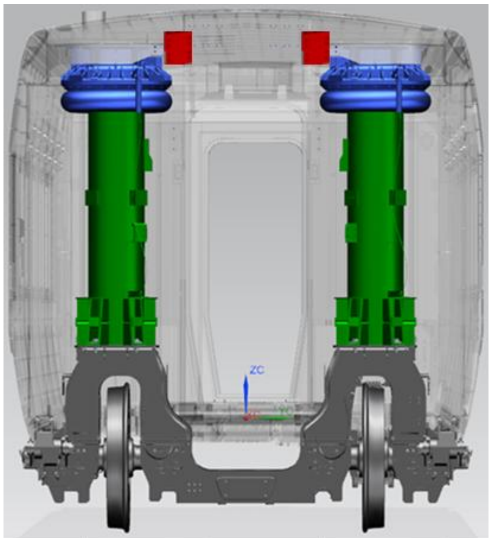


Figure 2 Supported end

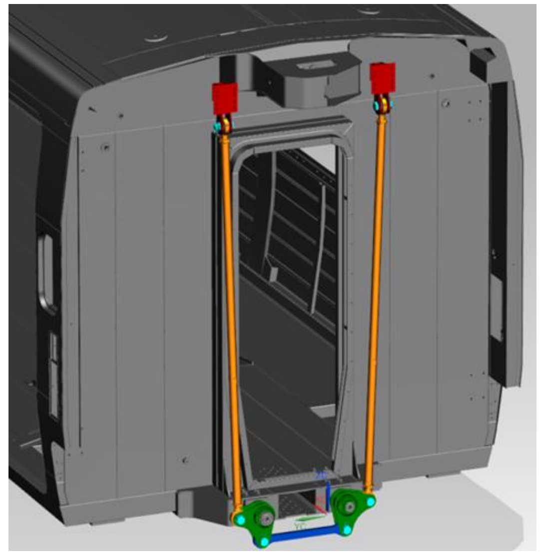


Figure 3 Suspended end

The supported end (Figure 2) rests directly on two towers (shown in green in Figure 2) that in turn rest on a rolling assembly (in grey). The suspended end (Figure 3) hangs from the adjacent supported end by means of two weight bearer bars (shown in orange). The two red pads indicate the attachments to the supported end. The location of that attachment is indicated in red in Figure 2.

1.2.2 *Description*

The sequence of the derailment can be better understood if the behavior of the train is explained by dividing it into the following three groups.

- First group: Siemens locomotive 1401, Talgo power car 7903, C1 7454, C2 7554, diner 7804 and bistro 7303.
- Second group: C3 7504, C4 7424, C5(7423 and C6 7422
- Third group: C7 7421, C8 7420, baggage 7102 and GE locomotive 181.

Taking all evidence into consideration, Talgo has concluded that the vehicles behaved as follows:

(a) First group:
(Siemens locomotive 1402, power car 7903, C1 7454, C2 7554, diner 7803 and bistro 7303)
According to the NTSB Preliminary Report[4] the train, led by the Siemens locomotive, reached the point of derailment, on the entrance spiral of curve 19A-1 at approximately mile post 19.9 at a speed of 78 mph. The speed board[5] (shown in Figure 4) limits the speed here to 30 mph.

[4] Preliminary Report Railroad Amtrak Passenger Train 501 Derailment DuPont, Washington December 18, 2017 RRD18MR001, posted on line

[5] In this case, the board shows that here the maximum allowed speed for Talgo equipment (T) is the same as that for passenger trains using conventional equipment (P).

Figure 4 Speed board marking the beginning of the curve

Figure 5 Point of Derailment

When it reached the curve, the locomotive derailed to the high side, slipped off the right side and rolled to its right until it reached a point next to the bridge. At that point it righted itself, returning to vertical. Figure 6 shows the state of the locomotive after the accident, displaying evidence that it was sliding on its right side.

Figure 6 Locomotive condition after the accident (right side)

Figure 7 Locomotive condition after the accident (left side)

Figure 8 and 9 show evidence of impact of the locomotive against the retaining wall to the right and the distant signal for the Nisqually control point, MP 21.3. (The debris at the right in Figure 8 is from the signal.)

Figure 8 Retaining wall condition after the accident

Figure 9 Wall and signal mast condition after the accident

Note that when the locomotive overturned, the Talgo equipment remained upright and coupled to the locomotive, which continued to pull it.

According to Talgo's dynamic calculations, due to their low center of gravity, the Talgo cars could have run through this curve at this speed without overturning. Further evidence (in addition to engineering calculations) supporting the belief that the locomotive had turned on to its side was provided by physical inspection of the damaged equipment during March, 2018, at Joint Base Lewis-McChord (JBLM). Ballast and dirt were found inside the right side of the locomotive, and drag marks were clearly visible on that side, indicating that the locomotive was on the ground during the accident.

Figure 10 Detailed view of locomotive coupler

Once the locomotive returned to a vertical position, the five cars in this group (power, C1, C2, dining and bistro) continued to follow it, descending on the right slope of the fill and finally stopping with the locomotive on the highway. When the locomotive hit the pavement, due to the unstable AAR couplers between it and the Talgo consist, the power car turned counterclockwise (as viewed from above) and separated from it.

Figure 11 Approximate route of the first group

(b) Second group:
(C3 7504, C4 7424, C5 7423 and C6 7422)
This segment of the train suffered compressive forces from both ends. From the front, it was due to the first group decelerating as it plowed through the woods, while from behind it was being pushed by the third group (C7 7421, C8 7420, baggage 7102 and locomotive 181). This situation caused the rotation of C3 7504 between the bistro car 7303 and C4 7424, causing the coupling between the bistro car 7303 and C3 7504 to fail. From the rear, C4 7424 continued to push and its coupling with C3 7504 failed. C3 (now traveling disconnected and sideways with its left side forward in the direction of travel) struck the concrete wall retaining the fill behind the north abutment of the bridge over the southbound lanes of I-5. The impact destroyed the left side of the car, which then rolled over onto that side as it fell down the embankment about 12 feet onto C2 7554 and dining car 7804. The C3 7504 truck (RRG-0050) remained near the supported end of this car after its separation.

At the bridge entrance, C4 7424 hit the walkway railing, generating the longitudinal cut observed on its right side (in the direction of travel). Under its own inertia and probably being pushed from behind, this car tore off a part of the bridge, falling down onto I-5. It turned upside down with the supported end towards the back and the suspended end forward. Due to the impact against the highway, this car's truck (RGG-0082) also fell onto I-5. It came to rest in the left lane under the bridge after being pushed there by a vehicle on the highway that struck it.

Cars C5 7423 and C6 7422 followed the same dynamics, breaking their couplings but remaining on the bridge, as by this time they had slowed considerably. The C5 7423, in the same way as C4 7424, tore off a part of the bridge, and its truck was hanging down from the bridge. It should be noted that C6 7422 turned nearly 180 degrees, with its suspended end to the front. Its truck (RRG-0062) separated from the car and is under C3 7504, which had turned a full180º, falling down the previously mentioned 12 foot slope.

(c) Third group:
C7 7421, C8 7428, baggage 7102
C7 7421,which lead this group, passed the point of derailment without derailing and remained on the track until forces from C6 7420, which had rotated, caused it to derail to the left of the track, falling down the subgrade onto C4 7424, by now lying overturned on I-5. At this point a truck hauling an ISO container on a chassis and traveling south on the highway impacted the C4 7424 (and scratched C7 7421). The truck pushed C4 7424 under the bridge and moved C7 7421 in the same direction, coming to rest beyond the bridge. The rolling assembly on C5 7423 remained attached, with one of its wheels hitting the right side of C7 7421, now below it. The C7 7421 truck (RRG-0032) separated from the car, falling on the right side of I-5. C8 7420 then derailed, being pulled by C7 7421. Only one end of baggage car 7102 (and all four axles of the rear locomotive 181) remained on the track.

Locomotive	Power	C1	C2	Diner	Bistro	C3	C4	C5	C6	C7	C8	Baggage	Locomotive
WDTX 1402	AMTK 7903	AMTK 7454	AMTK 7554	AMTK 7804	AMTK 7303	AMTK 7504	AMTK 7424	AMTK 7423	AMTK 7422	AMTK 7421	AMTK 7420	AMTK 7102	AMTK 181

Amtrak train 501 configuration

Figure 12 Final location of the equipment after the accident

The five pictures in Figure 13 provide detailed views of the positions of the cars after the accident.

Only locomotive 161 (at left) and rear end of baggage car 7102 (center) remain on the track

C7 7421 (center) rests on C4 7424 (upside down under the bridge). A wheel from C5 7323 (above it) has impacted the right side of C7

Bistro 7303 has followed the locomotive into the woods

Bistro 7303 Left side

C7 7421 rests on C4 7424 (upside down under the bridge)

Figure 13 Detailed views of damaged cars in situ

1.3 INJURIES

There were 83 people onboard Amtrak train 501, 81 in the passenger cars, including three members of the Amtrak crew and two Amtrak crew members in the lead locomotive.

The most relevant injuries are the three passenger fatalities in C3 7504, the car that hit the retaining wall of the bridge approach.

1.4 CONTRIBUTING FACTORS: Topography and Structures

The railroad runs parallel to a highway, Interstate 5 (I-5) prior to the curve where the accident took place. In this section trains run for about ten miles at the relatively high speed of 79 mph up to MP 19.9, where there is sharp curve (of about 720 foot radius) that diverts the railroad from its parallel orientation along I-5 and takes it across that highway on an overpass. The presence of this overpass (and the "bridge dump" fill approaching it) and the height difference between the track and the wooded area aggravated the consequences compared to an accident in an area without these features.

Figure 14 Height difference track-wooded area (1)

Figure 15 Height difference track-wooded area (2)

1.5 EQUIPMENT INSPECTION STATUS

Maintenance of Talgo S-VI train sets includes both Preventive and Corrective Maintenance

1.5.1 *Preventive Maintenance*

The Preventive Maintenance (PM) Plan consists of original equipment manufacturer (Talgo) requirements based on history of and experience with similar trainsets, maintenance requirements provided by vendors of systems and components, contractual requirements and all activities required by applicable rules and regulations (FRA, AAR, FDA, etc.). The PM Plan also includes the list of the activities (inspections, analysis and components replacements) and their frequencies. PM frequencies are specified in one of three ways: mileage, calendar time (primarily CFR) and actual hours of operation (e.g. engines and compressors). See Figure 16, below. All PM activities (inspections, replacements, etc.) are documented on Registers (RIs). The goal is to anticipate failures and consequently to determine when a system or component needs replacement before it is about to cause a service disruption.

TIME BASED OPERATIONS				
DAILY	MONTHLY	3 MONTHS	6 MONTHS	YEARLY

	MILES BASED OPERATIONS						
	IS	IB1	IB2	IM1	IM2	IM3	R*
Minimum mileage	4,250	18,750	37,500	112,500	337,500	675,000	1,350,000
Medium mileage	5,000	25,000	50,000	150,000	450,000	900,000	1,800,000
Maximum mileage	5,750	31,250	62,500	187,500	562,500	1,125,000	2,250,000

Figure 16: Maintenance Intervals

All mechanical and electrical RIs during the 90-day period prior to the accident were completed within the maintenance plan intervals. As per NTSB request, electronic copies of all those registers were uploaded to the NTSB database.

1.5.2 *Corrective Maintenance*

Corrective Maintenance (CM) is the response to reported defects or failures of components and/or systems on the trains. CM data collected is inputted by various sources such as the On Board Technicians (OBTs) ridding each train set on every trip, client issues reported by e-mail and defects detected during PM inspections. The CMs entered in the database (Casandra) and their status can be seen in real time from any computer, so they can be accessed prior to train set arrival at the maintenance shop. The OBTs also have a smart phone on each train set to contact (call or FaceTime) the subject matter experts in order to address any important (safety or reliability) issue. The trains are also equipped with a diagnosis system that monitors the main safety systems such as suspension, brakes, journal temperature and exterior door status. All safety related CM's are addressed prior to train set departure from the maintenance facility.

2 ANALYSIS

2.1 INTRODUCTION

This section discusses relevant information about the major systems studied in the follow up meeting at DuPont (WA). The Crashworthiness and Survival Factors Group consisted of individuals from the NTSB, FRA, Amtrak, Siemens and Talgo. During the meeting Talgo shared several documents to demonstrate that the Series VI meet all the requirements of 49 CFR Part 238 – Passenger equipment safety standards. In addition, it was recognized that the accident under study would be classified as a high energy event due to the speed involved (greater than 50 mph). It is important to note that the speed of the train when it derailed was 2.6 times the limit in the curve. Two additional factors greatly increased the severity of the accident: the existence of the overpass and the elevation difference between the track and the adjacent wooded area. The combination of these factors suggests how exceptional the accident was. After a careful the investigation and inspection of the cars at the JBLM site, Talgo is confident that the *Mt. Adams* behaved as well or better than might reasonably have been expected of conventional passenger equipment.

2.2 TALGO TECHNOLOGY AND SAFETY

This section describes various features unique to Talgo that are responsible for the excellent behavior of this equipment in a collision or derailment.

2.2.1 *Lower Center of Gravity (CG):*

As described in 1.1, the Talgo equipment was dragged off the track by locomotive, and the Talgo trainset avoided rollover of passenger cars at a speed of 78 mph., a speed 2.6 times the (30 mph) speed limit in that area. As the CG of Talgo trains is lower than that of conventional trains, they can run through curves at a higher speed without overturning. According to Talgo's calculations the *Mt Adams* would have remained on the track at 78 and even over 79 mph. This claim is based on overturning calculations using the following formulas and data:

$$a_{nc} = \frac{v^2}{R} - g \cdot \frac{h}{a} \qquad\qquad z_{cg} = \frac{a \cdot g}{2} \cdot \frac{1}{a_{nc}}$$

Where:

a_{nc}: Non compensated lateral acceleration (on track plane)
V: Train speed
R: Curve radius (about 717 feet)
g: Gravity
h: Super-elevation (3 inches)
a: Distance between wheel contact points (59 inches)
z_{CG}: Center of gravity

These equations show that for any equipment the maximum safe speed is inversely proportional to the height of the CG. Thus the low center of gravity Talgo trains provide higher safety levels compared to conventional equipment.

Figure 17 illustrates the difference of the height of the CG of a Talgo car and that of the locomotive used on Amtrak train 501 on the date in question:

Figure 17: CG height comparison between the locomotive and a Talgo car

2.2.2 *Light Weight*

The kinetic energy (E_k) to be dissipated in an accident comes from the motion of the train and is directly proportional to its mass (m) and to the square of its velocity (v).

$$E_k = \frac{1}{2}\, m\, v^2$$

Thus, at any given speed, a lighter train will have proportionally less energy to be dissipated compared to a heavier one. Lower energy dissipation reduces the damage to the car bodies and can be more easily (and completely) absorbed by features provided for that purpose. Gracefully absorbed energy reduces the acceleration experienced by occupants and thus their injuries due to "secondary impact velocity", the speed (and thus force) with which they are thrown into seatbacks, tables, bulkheads and other passengers during a rapid stop.

2.2.3 *Natural Tilting*

Mainline curves are usually provided with "super-elevation", meaning the outside rail is higher than the inside rail. The purpose is to keep the resultant force vector (R in Figure 18 below), the sum of the gravitational force (g in the Figure) and lateral (centrifugal) force, within the gauge of the track, thereby preventing the vehicle from tipping over to the outside of the curve. As seen in this figure, the resultant vector passes through the "high" (outside) rail. At this point the wheel load on the low rail will be zero and any additional lateral force will cause this vehicle to tip over.

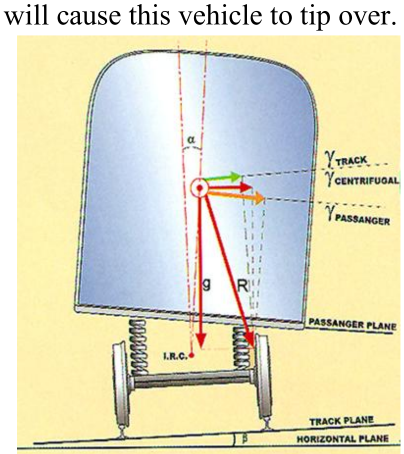


Figure 18 Vehicle at the point of overturning

Because it must be safe for trains of all types to stop on a curve, the amount of super-elevation is limited. The freight railroads[6] usually limit it to 5 or 6 inches. Depending on the suspension characteristics of the vehicle and the height of its center of gravity, it is safe to exceed this balance speed (up to a point), but as the excess speed becomes greater so does the unbalanced lateral (centrifugal) force and thus the discomfort to those on the train. The uncomfortable situation can become an unsafe one because it can cause a walking individual to be thrown off balance. Tilting has been use to mitigate this effect, and two types of tilting have been used. One method is "active" tilting, which is used by the *Acela* (between Washington and Boston). Hydraulic actuators controlled by curve sensors actively tilt the train. The other approach, the one used by Talgo, is to arrange the suspension geometry to provide natural tilting. Talgo achieves this result by locating its suspension above the center of gravity of the vehicle. Figure 19 illustrates the method and the result.

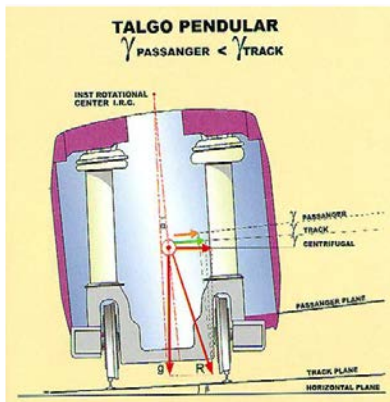


Figure 19 Talgo suspension geometry

2.2.4 *Collision Load Path Buff Strength*

In 1912, when most passenger cars, including Railway Post Office (RPO) cars, were of wooden construction, the US Post Office ruled that all RPO cars must be reinforced so as to be able to support "400,000 lb. buff on line of draft at half yield". Because the railroads felt they had to treat everyone on a passenger train at least as well as the postal clerks, the Master Car Builders' Association (and later the Association of American Railroads and still later the American Public Transportation Association) adopted a similar rule for cars to be used in conventional passenger trains. (Less strength was required for "motor cars" and similar lightweight equipment.)

The problem with this rule is (and had long been) that in a significant collision the load is not always (in fact rarely) applied simply "on the line of draft" which, of course, was the path provided for a draft (pulling) load, not a buff (pushing) one. While the rule may have been appropriate for the wooden cars common at the beginning of the 20th century, at the time of the Post Office rule steel cars were already being built (for service in the tunnels leading to and in Manhattan), and in the 1930s the Budd Company of Philadelphia introduced semi-monocoque construction into the field. Yet it was not until last November[7] that the FRA finally officially recognized this reality. While Tier I equipment (suitable for

[6] There is also a regulatory limit; 49 CFR 213.57(a) and 213.329(a) limit the outside rail to no more than 8 inches on low-speed track (up to 30 mph for passenger trains) and to 7 inches for the higher track classes.

[7] In a "Final Rule" published in the Federal Register on November 21, 2018 at 83 FR 59219 et. seq.

service at up to 125 mph in mixed traffic, i.e. on the general system), is still governed by the "line of draft" language, the new equivalent rule for Tier III (up to 125 mph in mixed traffic and 220 mph on dedicated right of way) takes the more relevant approach, requiring that the behavior of the structure meet one of three requirements under various loads, all of them to be "applied on the collision load path".

The *Mt. Adams* was put into service in December of 1998. At that time its "static end strength" complied with US industry standard for motor cars and similar lightweight trains. In May of the following year the FRA issued a new rule[8] requiring all passenger equipment to meet the industry standard for cars intended for use in conventional trains, thereby doubling the "end strength" requirement to "800,000 pounds applied on the line of draft without permanent deformation." As the *Mt Adams* (and four other Series VI sets) was already in service, Amtrak requested permission to continue operation under the "grandfather" clause in the new regulation. The FRA studied the safety implications of this request, consulting with the Volpe Center, (the US DOT R&D organization) and considered studies performed by the Arthur D. Little company under contract with Amtrak. The FRA granted the request, but with requirement for some modifications, which Talgo quickly incorporated. These changes are described later in this document (in Sections 2.4.2 and 2.4.3)

In any case, examination at JBLM revealed no damage (including even minor plastic deformation) due to compressive forces.

2.2.5 *Radial Axle Positioning*

Conventional railroad equipment steers through the taper of the wheel tread (the different circumference between the flange and field side of the wheel) and, when that correction is insufficient, by flange contact. This method over corrects at high speeds, resulting in hunting, and produces frequent flange contact at any speed, resulting in wheel flange and rail gauge face wear. Talgo rolling assemblies do not have an axle connecting the wheels on each side of the car. They are free to rotate at different rates and thus differential circumferential steering is not available. Instead the axis of the wheels is maintained in alignment with the radius of the curve (or perpendicular to the rail on tangent track) as shown in the arrangement depicted in Figure 20. The perspective view at the left shows that the lower (green) and upper (blue) bars act through the lever (red) attached to the bearing box to maintain the axle mid-way between the two car bodies, as shown in the schematic at the right of the figure. The axis thus bisects the angle between the cars and remains aligned with the radius of curvature. While this steering had no direct relevance to the behavior in this accident, the mechanism used to accomplish it provide additional car-to-car and car-to truck attachment elements.

[8] Federal Register, May 12, 1999, V64, No. 91, page 25540 et. seq.

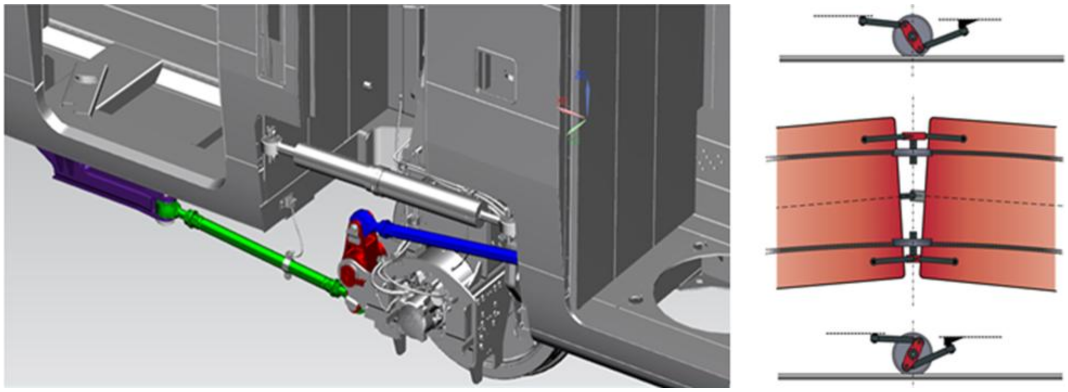


Figure 20 Talgo radial positioning system

2.2.6 *Overturning resistance*

The connections between Talgo cars use several connecting elements and stops, all of which provides a higher resistance to rollover and buckling (lateral displacement) than is found on conventional North American equipment. When a Talgo car tries to overturn from its center of rotation, which is located above the roof (represented as orange point in Figure 21), and exceeds the lateral clearance, the side stops (blue arrows in Figure 21) limit the rotation. If the allowable rotation of the bell crank is exceeded (see 1.2.1), the weight bearer bars that connect suspended ends to supported ends introduce vertical forces (red arrows in Figure 21) to limit the rotation. Due to these forces, during a rollover each car rolls a bit less than the one ahead of it, repeating the process until the point was reached at which there was no tilting at all, and the entire train works together to keep all cars upright.

Loads in weight bearer bars **Lateral stop reactions** **Center of rotation**

Rotation of first car **Rotation of adjacent car**

Figure 21 Schematic representation of forces in overturning scenarios

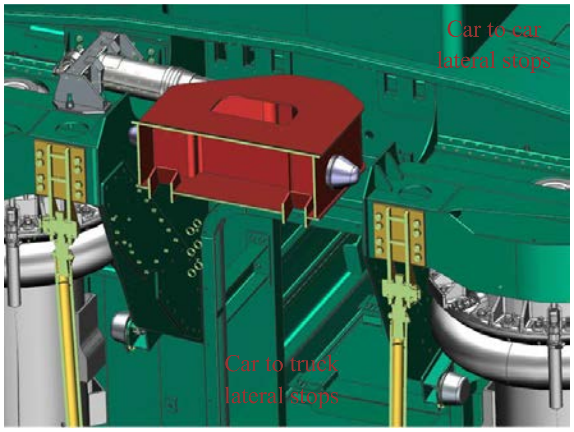


Figure 22 Overturn prevention stops at the roof

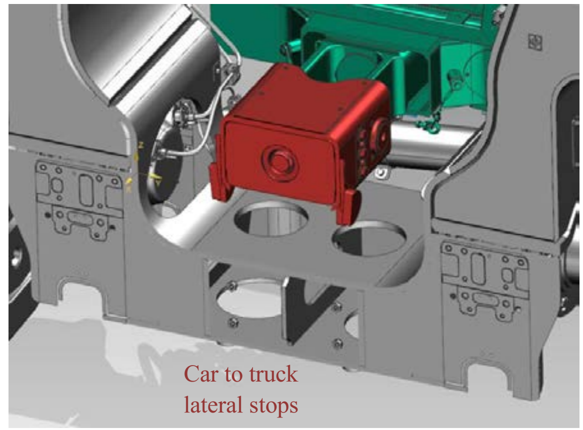


Figure 23 Overturn prevention stops below the floor

These numerous points of contact between coupled cars limit to a very small amount the difference between the lean angles of two adjacent cars. Thus, as we often point out, "When it is coupled, to roll a Talgo car it is necessary turn over the whole train." The July 3, 2017, derailment at Chambers Bay, Washington (Figure 24), illustrates this characteristic. Section 3.2 provides a more detailed description

Figure 24 Chambers Bay, Washington, July 3, 2017.

2.3 CRUSHING ANALYSIS, TALGO VI VERSUS CONVENTIONAL CARS

2.3.1 *Basic Concepts*

During a collision the following parameters greatly influence the consequences of the accident:

- The structure of the vehicle has a large effect on the forces and accelerations experienced by the passengers. The most important vehicle parameters in this regard are their stiffness and energy absorption capacity.
- The deceleration experienced by the vehicle (and thus its passengers) determines the severity of the accident.
- The kinetic energy involved in the collision is a function of the mass and the speed.

$$E_k = \frac{1}{2}\, m\, v^2$$

As Talgo cars have a lower mass compared to conventional cars the energy to be dissipated is proportionally less.

- To completely stop the vehicle, all the energy must be dissipated. As we all know, "energy is neither created nor destroyed, only transformed". When the collision is against a very stiff object, such a concrete wall (or a head-on collision with an identical train running at the same speed), all the energy will be absorbed by the vehicles. When the structure does not deform in a controlled manner, the collision can produce very high decelerations, which will be experienced by the occupants and are thus likely to cause severe injuries to them.
- The kinetic energy is absorbed by deformation of the structure.

$E_k = F \cdot d \quad and \quad F = m \cdot a$

Thus

$\boldsymbol{E_k = m \cdot a \cdot d}$

$\frac{1}{2}mv^2 = m \cdot a \cdot d$

Thus:

$a = \frac{v^2}{2 \cdot d}$

- Talgo cars are made of aluminum instead of steel which is typically used for conventional cars. It results in lower mass and higher deformations.

The following conclusions result from these equations:

1. Since the Talgo cars are lighter than conventional cars the kinetic energy involved in the accident is proportionally lower.
2. Since the larger the deformation in the structure, the lower the deceleration experienced by the passengers, large deformation is desirable; however, it is important that this deformation occurs in a controlled manner and location so that the occupied volume (survival space) remains relatively intact.

The favorable deformation characteristics of the Talgo equipment were described in a 2001 Arthur D. Little Safety Study, which is discussed in the next section. It leads to the ultimate conclusion that in the accident, the Talgo equipment both contained less kinetic energy than conventional equipment and also had a better ability to effectively absorb that energy.

2.3.2 *Arthur D. Little Safety Study.*

In September of 2001 the consulting firm Arthur D. Little prepared and documented a study for Amtrak regarding the safety of the Talgo VI trainsets. More specifically, the objective of the study was to obtain a better assessment of the crashworthiness of the Talgo VI trainset relative to the crashworthiness of conventional trains. This study arrived at the following (summarized) conclusions:

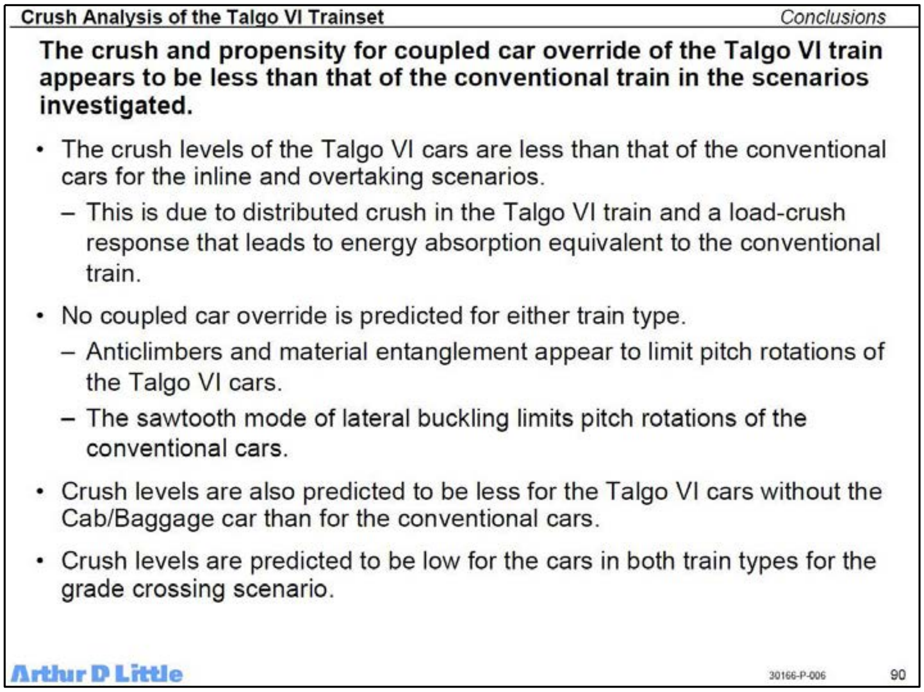
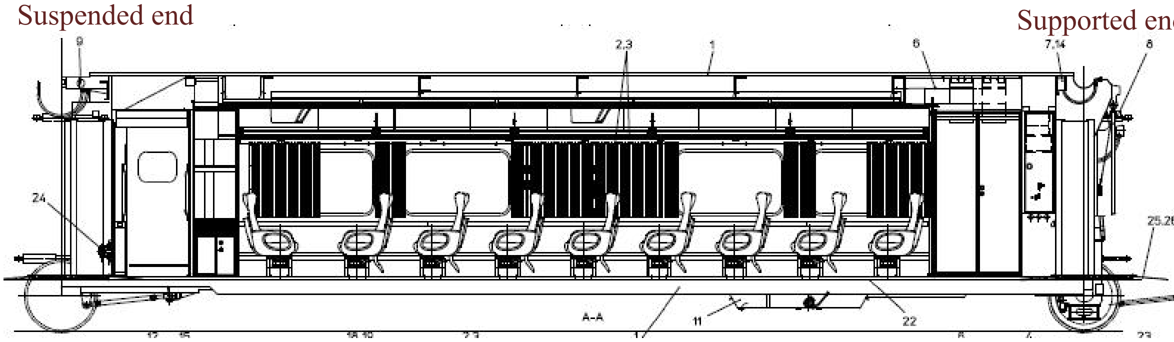


Figure 25 Arthur D. Little conclusions

One of the key characteristics of Talgo equipment that becomes important during a collision is distributed deformation along the length of the train. In essence, it results in a series of independent car to car impacts that produce deformations to end and intermediate cars located at the ends of the cars. It should be noted that not only are the end (baggage and power) cars completely unoccupied, but also both ends of intermediate cars are also unoccupied (see Figure 26).

Suspended end

Supported end



Vestibule
(Unoccupied volume)

Equipment cabinets
(Unoccupied volumes)

Figure 26 Unoccupied spaces in a typical Talgo Series VI passenger car

The maximum passenger car end crush is predicted to be greater in the conventional train than in the Talgo Series VI train. For the road crossing scenario they are similar. In that study the majority of the crush damage is predicted at the lead face of the locomotive. The collision energy is much lower and as consequence the deformations are also lower.

The pictures in Figure 27 show the deformation of a Series VI intermediate car. Note that in the

pictures the suspended (vestibule) end is labeled “*portapesos*” and the suspended (blind) end, “*muelles*”.

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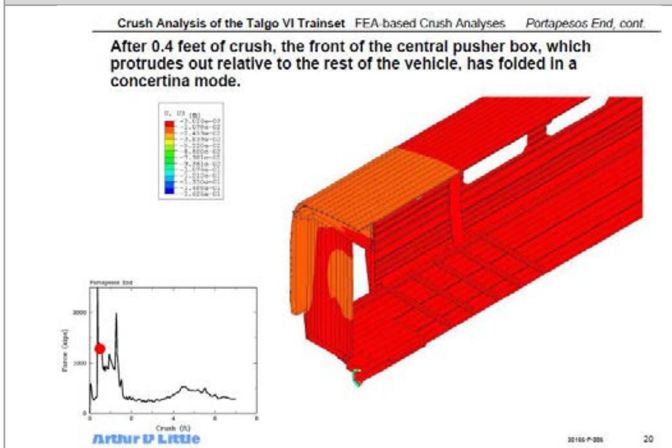
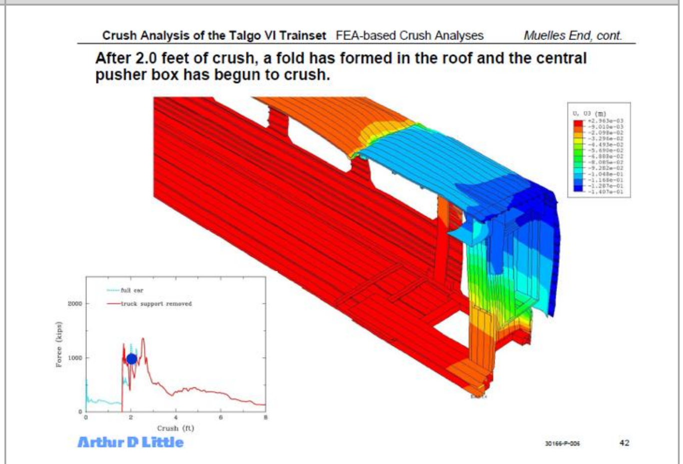
<tr><th>SUSPENDED END</th><th>SUPPORTED END</th></tr>
<tr><td>

”</td><td>
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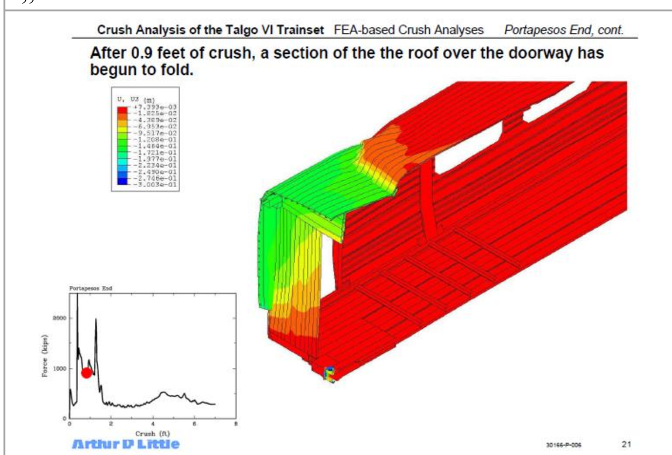
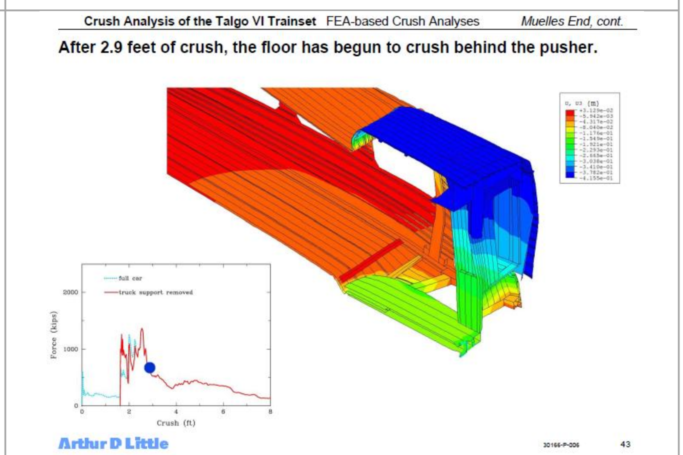
<tr><td>
</td><td>
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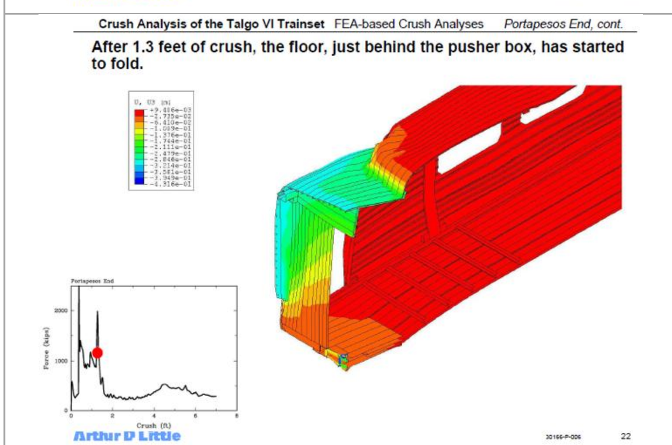
<tr><td>
</td><td></td></tr>
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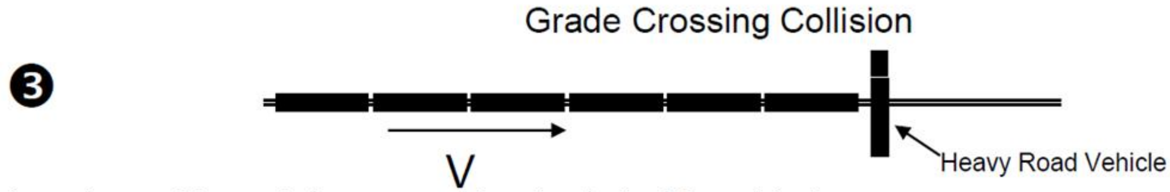
Figure 27 Arthur D. Little crush analysis

The Arthur D. Little study included three collision scenarios: (a) two road crossing collisions, one at 40 mph and another at 50 mph, (b) two of like trains head-on at 40 and 50 mph closing speeds and (c) one train hitting the rear of another at a closing speed of 25 mph.

a. Road crossing scenarios

This collision was studied at 40 mph and 50 mph (the latter a "high energy event")



The majority of the crush damage is predicted at the lead face of the locomotive. This scenario presents a lower energy than the train-to-train scenario (about 6 times lower).

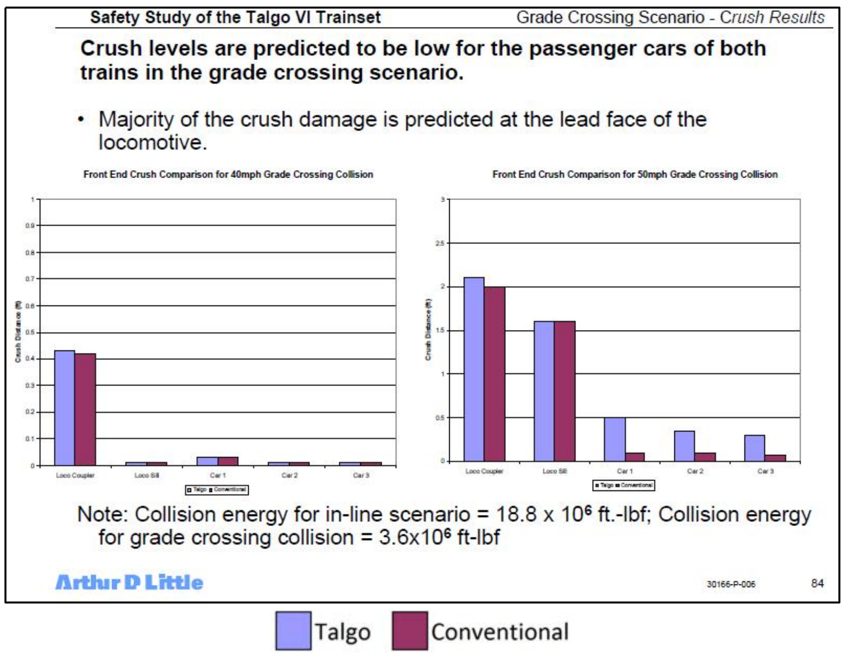
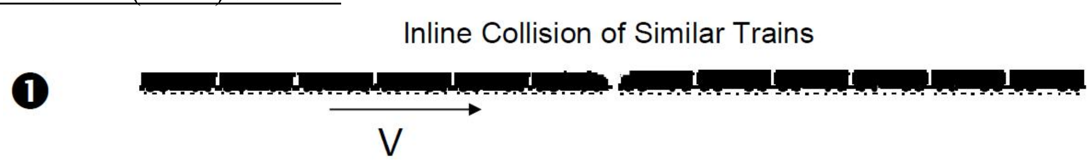


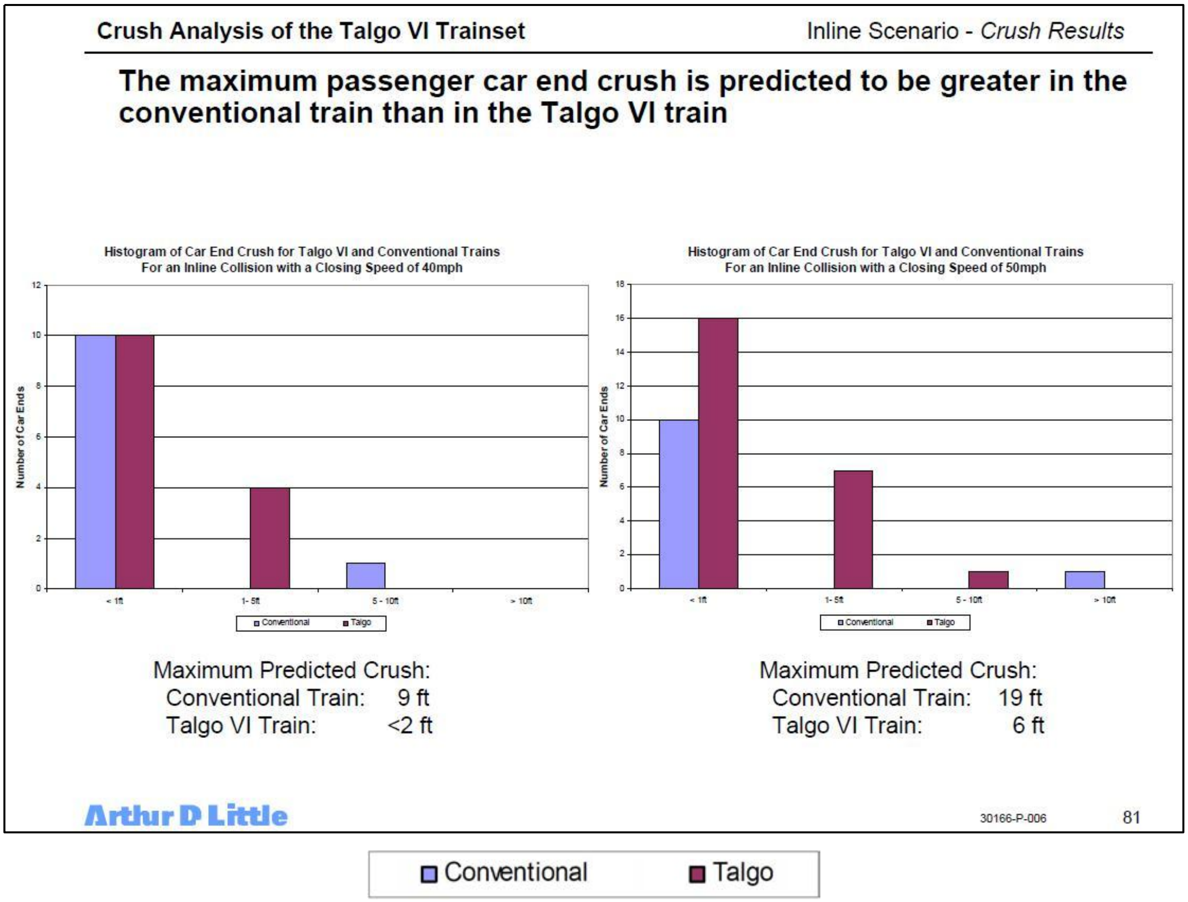
Figure 28 Crush at various vehicles, 40 and 50 mph road crossing collisions

At 40 mph the behavior of Talgo Series VI and conventional trains is similar, but the difference becomes significant in high energy events (50mph). As shown in Figure 28, the deformation level in the first occupied Talgo car ("Car 2") is less than 0.4 feet, and as can be seen in the pictures in Figure 27, at that deformation level the survival space (the occupied volume) is not affected.

A general rule can be taken from the Arthur D. Little analysis: Talgo Series VI trains produce higher deformations along the train, absorbing energy and preserving survival space for the passengers. In essence, it results in a series of independent car-to-car impacts.

b. Train-to-train (in line) scenarios





Note that y axis is number of car ends (0 to 12 or 18); x axis is in feet: <1, 1-5, 5-10. and >10

Figure 29 Crush at various vehicles, 40 and 50 mph train-to-train collisions (inline)

c. <u>Scenario 3. Train-to-train (overtaking)</u>

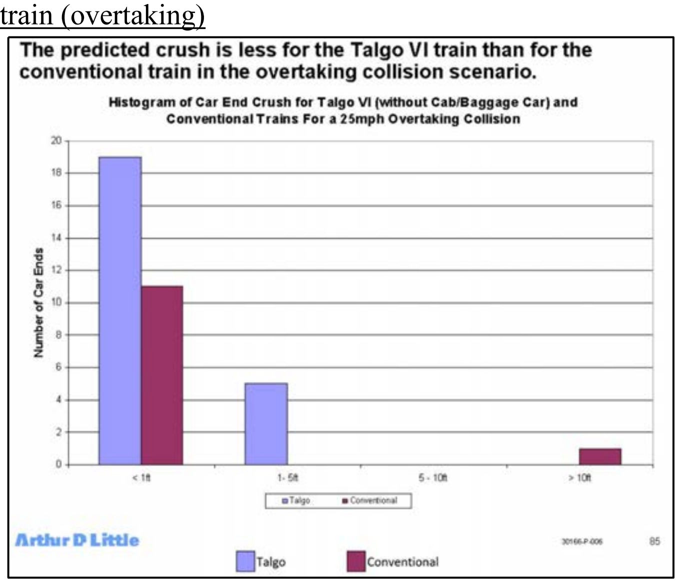


Figure 30 Crush at various vehicles, 25 mph train-to-train collisions (overtaking collision)

In this scenario only five Talgo ends crush as much as 5 feet; one conventional end crushes more than 10 feet.

During the accident power car 7903, C1 7454, C2 7554, dining car 7804 and bistro 7303 suffered in-line collisions confirming that Talgo trains distribute deformation along the train as anticipated in the Arthur D. Little report. The pictures that follow show evidence of the in-line deformations.

Figure 31 power car 7903. car to car interactions

Figure 32 C1 7454. Car to car interactions

Figure 33 Diner 7804. Car to car interactions

There are no additional crush analyses available for the Talgo Series VI. Usually, safety standards

consider speeds up to 30 or 35 mph for train to train collisions (in-line or overtaking scenarios), but not higher speeds. The Talgo Series VI is an FRA "Tier I" trainset (one designed for up to 125 mph in mixed traffic). The next level is Tier II (mixed traffic up to 150 mph, recently increased to 160). Even for this higher speed Tier II equipment, the requirement (at 49 CFR 238.403) addresses behavior in a collision (with a similar, stationary, train) at only 30 mph.

Another example is APTA PR-CS-S-016-99, Rev. 2, ANNEX B.4. 2 Full-scale rail collision testing, which describes the requirements for testing performance of seats. The maximum speed required for this test is just 35mph.

For the "Crush Analysis" report[9] the speeds considered in collision scenarios were much more challenging, being 40 and 50 mph. It should be noted that, all else equal, a collision at 50 mph involves 2.8 times the energy of one at 30 mph.

2.4 GENERAL PERFORMANCE OF *MT. ADAMS* TRAIN SET

As discussed in Section 1.2.2, analysis of the accident indicates that the level of damage which occurred is understandable given the severity of the accident and does not indicate that the equipment performed poorly.

2.4.1 *Strength Assessment of Talgo Series VI*

The car body structures of Talgo Series VI cars were calculated by Finite Element Analysis methodology in accordance with 49 CFR Part 238, UIC 566 and Talgo requirements to assure all requirements were met. These requirements are summarized in the following table:

STANDARD	LOAD CASE
UIC 566	➢ Coupler compression* ➢ Coupler traction ➢ Vertical acceleration (1.3g_z) ➢ Vertical acceleration (1.3g_z) + coupler compression. ➢ Vertical acceleration (1.3g_z) + coupler traction. ➢ Vertical acceleration (1.3g_z) + compression weight bearer support 90 kip (400kN)
49 CFR PART 238	➢ § 238.203 Static and Strength* ➢ § 238.205 Anti-climbing mechanism ➢ § 238.211 Collision posts (only for end cars) ➢ § 238.215 Rollover strength ➢ § 238.217 Side structure ➢ § 238.219 Truck-to-car-body attachment ➢ § 238.233 Interior fittings and surfaces
TALGO requirements	➢ Twisting torque over the carbody. 620kip-in (70kNm) ➢ Lifting load case. Tare mass + truck weight attached to the car.
* *Met under Grandfathering conditions. Specific section 2.4.4*	

Table 1 Load cases. Car body structure

The information about the Talgo Series VI equipment that was shared with the Crashworthiness Group shows that it meets the requirements of 49 CFR 238 after the modifications required by the FRA Final Decision.

[9] Safety Survey of the Talgo VI Trainset: Crush Analysis, September 27, 2001, A.D. Little, Inc. report to the Volpe Center., Ref. 30166

2.4.2 *Truck Attachment*

The normal attachment between the rolling assembly (truck) and the two adjacent units (cars) is achieved through the upper and lower guidance arms. These guidance arms are 51 mm (2 inches) OD with a 5 mm (0.20 in,) wall thickness. The ultimate tensile load of each is 73,000 pounds (calculated analytically). Since there are four arms the total retaining force is about 292,000 pounds. In addition, each rolling assembly is connected to the tower supports (of the adjacent supported end) by two steel cables. Each has an ultimate axial load of 3344 lb., a total of 6889 lb. for the two cables.

The US version of the Series VI also has six additional securement straps, two upper straps around the vertical towers to car body and four lower straps around hooks on the rolling assembly and the car body.

Since the rolling assembly is confined between two cars, the weight bearer bars and the articulated joint must be severely damaged to allow it to detach completely from the trainset.

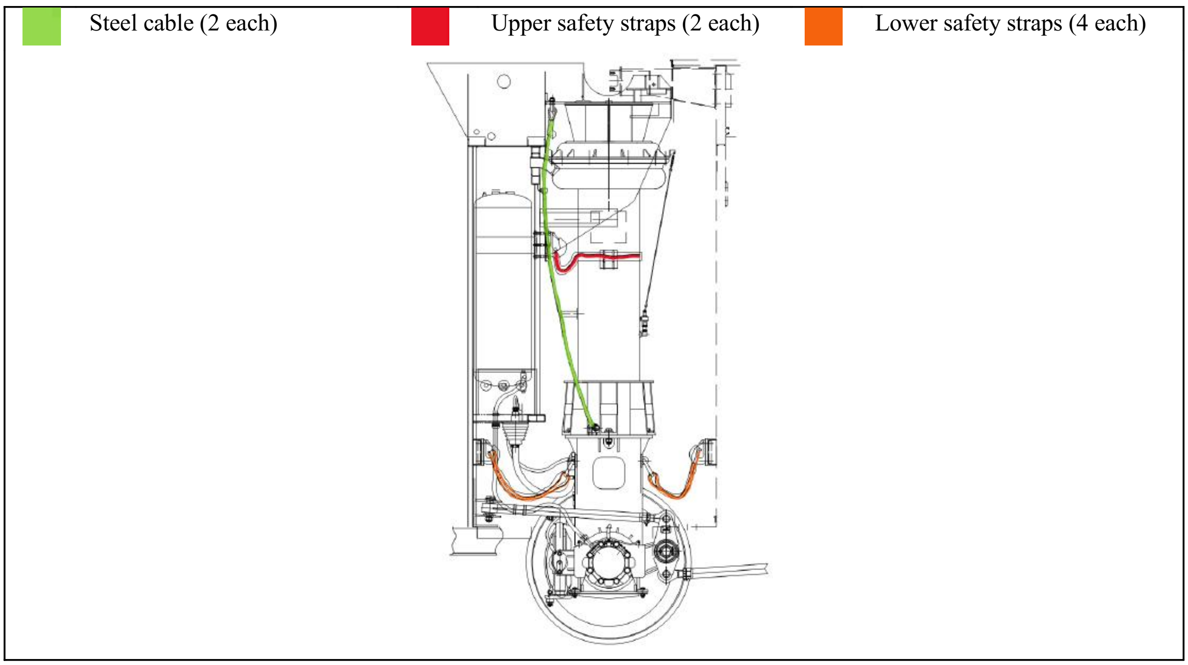


Figure 34 Illustration of a Rolling assembly and its attachment system

This design was presented and validated in the document "SAFETY STRAPS AND WEIGHT BEARER BARS – FURTHER INFORMATION". In this document the minimum safety factor is shown to be 4.48. In this report the ultimate load for straight lifting (simple tension) is used, but the manufacturer's data indicate that this load should be doubled for a "basket configuration" (Figure 35). As shown in Figure 36, in the actual application the upper straps surround the tower, and the lower straps surround the hooks attached to the rolling assembly.

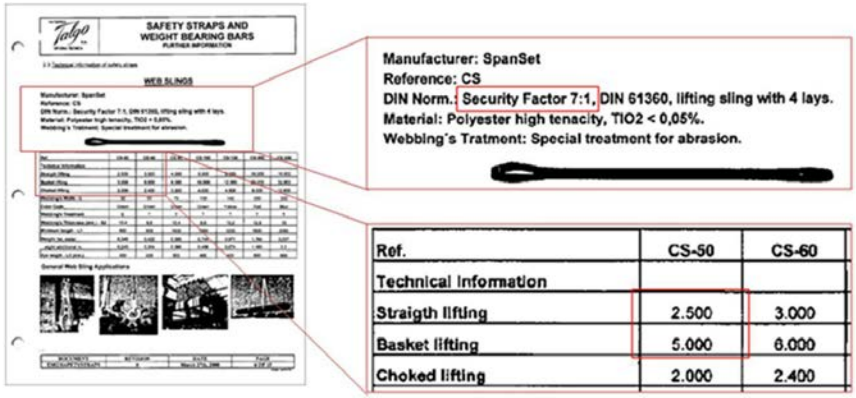


Figure 35 Technical datasheet

Figure 36 Strap detail

For the truck to detach completely from the cars all the attachments must be broken. This fact implies that the forces involved in the process must be higher than the 250,000 pounds required by 49 CFR § 238.219.

But it is important to recognize that this problem is not unique to Talgo. It is the case with all passenger cars regardless of the manufacturer. There are several recent accidents that provide examples of rolling assembly detachment during even under less unfavorable conditions. (This fact is documented in Section 3 along with other failure modes such as. decoupled cars, turnover events and large lateral displacements**).**

In addition, we note that the very light Talgo truck will be retained in place under much higher accelerations that can be resisted by the attachment of the very heavy conventional trucks, which are restrained up 250 kip of force in horizontal plane, about 12.5g for most trucks (and less for some, for example, those with Spicer generator drives).

$$F = ma \rightarrow a = \frac{F}{m}$$

At the given F (250 kip), as the mass decreases, the permissible acceleration becomes higher. Due to this fact it is clear that the Talgo truck attachment is safer than any other in the US.

It is, however, not clear how much securement would have been required to retain the rolling assemblies under the unknown accelerations and forces experienced at DuPont. Figure 37 provides an idea of the forces involved in the accident.

Figure 37 Deformed rolling assembly, made of ½ in. steel plate

To increase the safety level of the rolling assembly attachment, Talgo proposes the addition of new straps to increase the retention capability beyond the FRA requirement. This modification is discussed in Section 5.

2.4.3 *Weight Bearer Bar System*

The weight bearer bar system is a very safe system, as it is both redundant and over-designed. These bars are always under tension except in very unfavorable conditions (when performing their anticlimbing function in a collision).

The UIC design was modified to comply with the requirements of 49 CFR 238.205 which states that all passenger cars must have an anticlimbing system capable of resisting a vertical force of 100,000 pounds. This modification was calculated and verified in the document "MODIFICATION OF THE WEIGH-BEARING BARS MECHANISM". In this modification the outside diameter was increased from 2 inches with a wall thickness 0.31inches to an outside diameter of 2.5 inches with a 0.4 inch wall thickness. This modification was validated by FEA, analytical calculations and tested in late 1999 (Figure 38), within a series of tests conducted in the Rail Dynamics Laboratory at the Transportation Technology Center, Inc., a subsidiary of the Association of American Railroads, in Pueblo, Colorado.

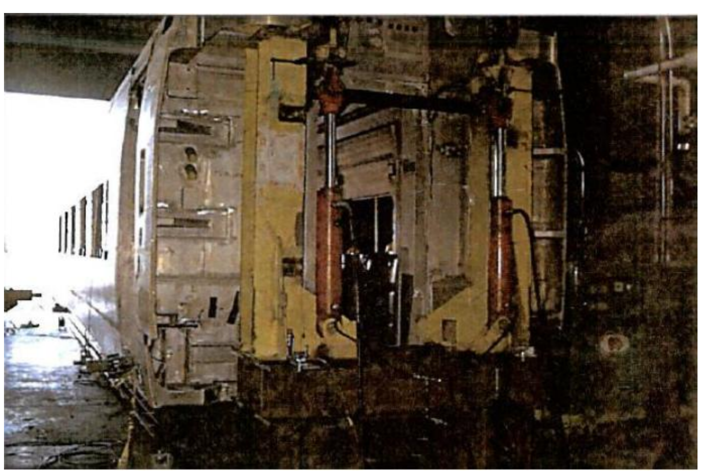


Figure 38 Illustration of anticlimbing test

Under the loads indicated in CFR the most critical condition is the buckling failure of the bars. This condition was apparent in several cars such as diner 7804, bistro 7303 and C5 7423. This effect is shown in Figure 39 to 41, where no failures of attachments are detected but severe deformations of suspension tower supports did occur. These deformations show that the forces produced during the accident greatly exceed the 100,000 pounds required by the current regulation.

Figure 39 diner 7804 weight bearer bar buckling

Figure 40 bistro 7303\ weight bearer bar buckling

Figure 41 C5 7423 weight bearer bar buckling

Each weight bearer bar can withstand a tensile load of 170 kips. This value was calculated analytically as follows:

$$F = \sigma_R \cdot A$$

Where:

σ_R: Yield for S355 steel = 65.27 kpsi (conservative value).

A: Section. 2.605 in^2

r_{ext} (OD) = 1.25 in

r_{int} (ID) = 0.856in

The structure to which the weight bearer bars are attached can carry a vertical tensile load of 150 kip at each support, 300 kip total. The weight of a passenger car is about 33,000 pounds, and thus the weight at each end is about 16,500 pounds.

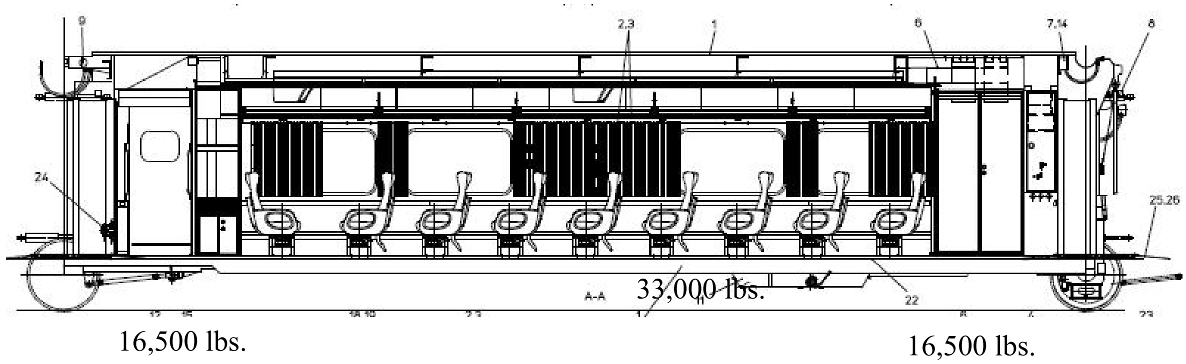


Figure 42 Load distribution

Assuming that for some reason one weight bearer bar has failed and only the remaining bar is left to carry the entire weight of the suspended end of one car, the safety factor of the weight bearer bar under the weight of the car is greater than 9 (150 kips / 16.5 kips). Thus the weight bearer bar system is very safe, having both a very high safety factor and redundancy.

In some cars the aluminum plate where the weight bearer bars were attached had been torn off from the tower support. This failure was caused by very high forces as can be inferred from Figure 43 and 44, where the car body structure was severely deformed by these vertical loads.

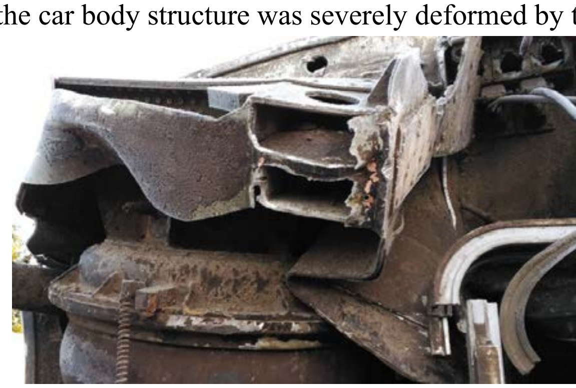


Figure 43 C7 7421 tear off detail

Figure 44 C7 7421 tear off detail

2.4.4 *Static End Strength*

As explained in Section 2.2.4, the *Mt. Adams* had been operating under a "grandfathering" provision for two decades due to a change (shortly after the equipment had entered service) in the FRA

requirement for "static end strength". Because the rapid deceleration of the front portion of the train as it plowed through the woods likely produced high buff loads it is instructive to see how the structure handles them. Inspection of the equipment at JBLM revealed no damage, including even minor plastic deformation, outside of the "line of draft" (see Section 2.4.5) due to these buff loads.

2.4.5 *AAR Automatic Couplers*

The couplers on Talgo end cars are Type H Tightlock couplers in accordance with AAR (now APTA) standards (Talgo Technical Specification ET-0213). This coupler on power car 7903 was broken due to the forces produced when the buff forces (produced by the decelerating locomotive) caused lateral forces that rotated power car 7903. Post-accident inspections reveal deformations consistent with torsional and bending loads in the power car and the locomotive. Figures 45 and 46 show torsional and bending deformations on the power car coupler. Figure 47 and 48 show the torsion effects on locomotive coupler.

Figure 45 Power car 7903. AAR coupler (1)

Figure 46 Power car 7903. AAR coupler (2)

Figure 47 Loco 1402. AAR coupler (1)

Figure 48 Locomotive 1402. AAR coupler (2)

The unstable pinned connection between the locomotive's coupler and its draft gear yoke is evident in Figure 47. The result was that under heavy buff loading the coupler moved far to the right, displacing the front end of power car 7903 in that direction and allowing C1 7454 to push the rear end of that car to the left, rotating it 90 degrees clockwise (as seen from above) and into its final position.

No damage was found on the couplers between baggage car 7102 and locomotive 181.

2.4.6 *Articulated Joint Coupler*

Articulated connections were subjected to various types of loads depending on the car to which they were attached. The articulated joint between power car 7903 and C1 7454 was broken due to the rotation of the power car described in 2.4.5 above. For the connections between C1 7454, C2 7554, diner 7803 and bistro 7303, the couplers were subjected mainly to compressive forces, and it was necessary to cut off the bolted supports to release the cars.

Figure 49 C1 7454. Coupler detail supported end

Figure 50 C2 7554. Coupler detail suspended end

Figure 51 diner 7804. Coupler detail suspended end

According to the accident sequence described in 1.2, the coupler between bistro 7303 and C3 7504 broke when the cars ahead of C3 7504 decelerated and the cars behind it, still on the track, kept pushing. Figure 52 shows the effect of the very high forces that broke the beam to which the coupler is attached.

Figure 52 C3 7504 Coupler detail, suported end

As was the case between bistro 7303 and C3 7504, the couplers between C4 7424 and C5 7423, C5 7423 and C6 7422 and C6 7422 and C7 7421 also failed due to rotation of the cars. C7 7421 remained attached to C8 7420, and the two stayed in line and upright.

Under these conditions, it is likely that conventional cars would also have rotated with one falling to the highway.

2.4.7 *Rollover and Side Impact Strength*

It should be noted that the train did not experience any rollover in this accident. While the first car in conventional trains tends to overturn when run through a curve at excessive speed as seen in Section 3, the *Mt Adams* did not overturn. (See the final position of C1 7454, C2 7554, diner 7804 and bistro 7303.)

The Talgo Series VI complies with the requirements of 49 CFR 238.215 and 238.217. The assessment of these requirements can be found in document "LPG0017T-Car rollover strength" and "16 SIDE IMPACT STRENGTH - Analytical analysis", respectively.

According to the accident sequence described in 1.2, C3 7504 received a high speed side impact against the overpass approach fill retaining wall, causing extensive damage at that point (and possible immediately following this collision). As can be seen in Figures 53 through 56 below, this extensive damage could not have been produced by the truck that detached from C6 7422, three cars to the rear, but it could have easily been produced by impact with the concrete wall. One block from this wall, which was partially demolished by the impact for the train, is visible immediately to the left of the detached truck in Figure 56. All three deceased passengers were in this car.

Figure 53 C3 7504. Side impact evidence (1)

Figure 54 C3 7504. Side impact evidence (2)

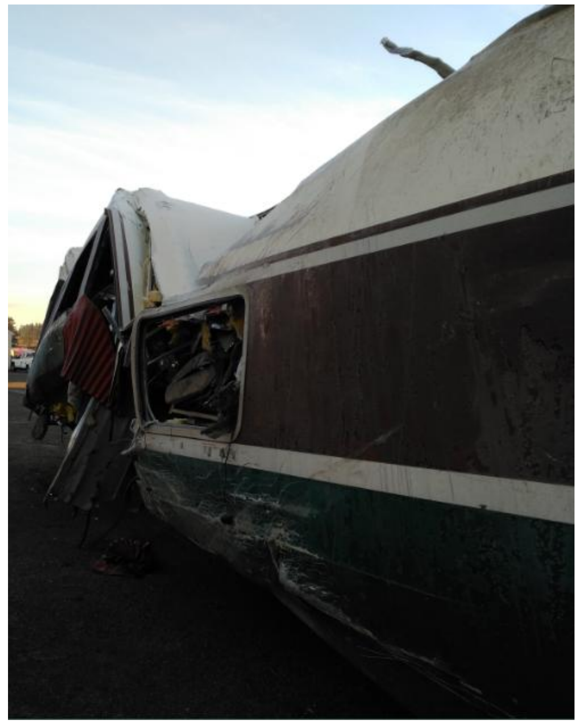


Figure 55 C3 7504. Side impact evidence (3)

Figure 56 C3 7504. On site

During the accident sequence, C4 7424 was subjected to much more severe side and roof impacts than those required by the CFR. The car fell onto its roof under dynamic, not the "quasi static" conditions of 49 CFR 238.215, and then, while it was resting on its roof and supporting some additional weight from C7 7421, substantially increasing the vertical load, it was struck on the left side by the combination tractor semitrailer that was southbound on I-5, the condition anticipated by 238.217 for an otherwise

undamaged and unloaded structure.

This combination of events is not addressed by the requirements of 49 CFR 238.

Figure 57 C4 7424. Side impact evidence (1)

Figure 58 C4 7424. Side impact evidence (2)

Figure 59 C4 7424. Final position (1)

Figure 60 C4 7424. Final position (2)

According to the investigation, a total of 11 passengers were in C4, none fatally injured.

2.4.8 *Collision Posts*

The Talgo Series VI designed was modified to comply with the requirements 49 CFR 238.211 Collision posts. The strength assessment for the collision posts can found in report "LPG0003T-Baggage (FEA)(03.16.2018).pdf"

While severe damage to the end fairing of power car 7103 was apparent during the inspection at JBLM, the steel structure that forms the collision posts was found to be undamaged. (See Figures 61 and 62)

Figure 61 7903 Power car. End detail (1)

Figure 62 7903 Power car. End detail (2)

2.4.9 *Seats*

The seating currently installed[10] in the Talgo Series VI train sets was tested at Simula Inc., Phoenix, Arizona, in August of 2005 in accordance with 49 CFR §238.233 and APTA SS-C&S-016-99 as indicated in "Kustom Seats - Dynamic Row to Row Sled Tests".

According to the investigation, some seats rotated due to various causes, but no defects attributable to design or maintenance were found. In C5 7423 the root cause was the lateral collision against the overpass. Metal debris from the bridge was found in this car. That damage caused the rotation of some seats, some of which were actually fixed (non-rotating) seats. In C4 7422 and C2 7554 rotated seats were examined with no defects found.

Figure 63 C5 7423 Metal debris intrusion

The rotation of seat 4C in C2 7554 was clearly caused by the deformation of the left side after C3 7504 came to rest on it. That deformation is clearly visible in Figure 64.

Figure 64 Left side deformation of C2 7554

Deformation of the sides broke the seats loose from their bases, allowing them to rotate; no defects of the attachment of the seat bases to the car body structure were found.

2.4.10 *Windows*

As required by 49 CFR 223.15 Talgo Series VI passenger cars each have four emergency windows. As an example, Figure 65 shows the emergency window locations in a business class car.

[10] The original seating was replaced in 2008 -09 with new seats manufactured by Kustom Seating Unlimited of Chicago. At that time the attachment was also modified, moving it from the "floating" floor to direct structural attachment, the normal configuration in North America.

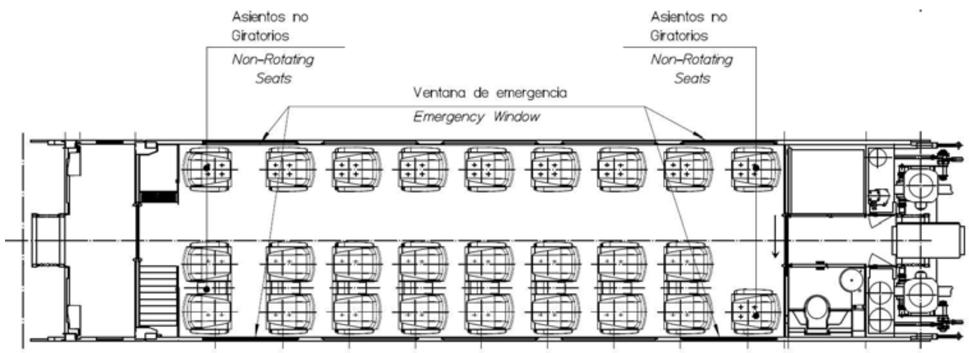


Figure 65 Emergency window locations, business class car.

These windows are FRA type II in accordance with 49 CFR 223.17 and were tested under ballistic and large object impacts as certified in "glazing test" report. Figure 66 and 67 show the required marking on these side windows.

Figure 66 Glass marking. Type II

Figure 67 Glass marking. Manufacturer and material identification

Analysis of previous accidents of conventional trains reveals that in several cases the loss of side glazing caused fatalities; it was not the case on the *Mt. Adams*. Figure 68 is an extract from an Amtrak equipment evaluation.

- *Positive* Does not appear any loss of side glazing contributed to passenger fatalities

Figure 68 Extract from an Amtrak document

It should be noted that glazing designed for removal from the outside (by emergency responders) is very likely to be removed by ballast as a car slides on its side after a derailment. While no fatalities were attributed to this phenomenon in this accident it has been common cause of fatalities in similar accidents.

2.4.11 *Final Analysis and Tests*

Talgo cars and trucks have several connections (Figures 69 - 72). For all to have failed, very high forces must have been involved.

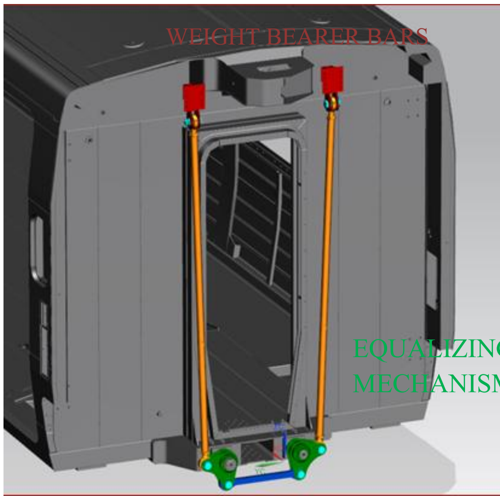


Figure 69 Weight bearer bar system

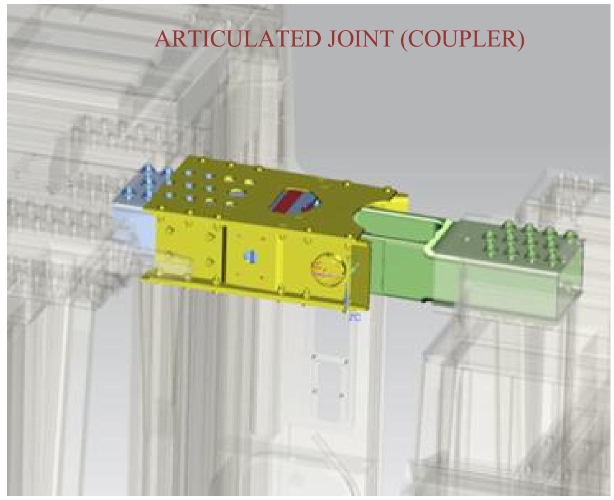


Figure 70 Articulated joint coupler (bottom view)

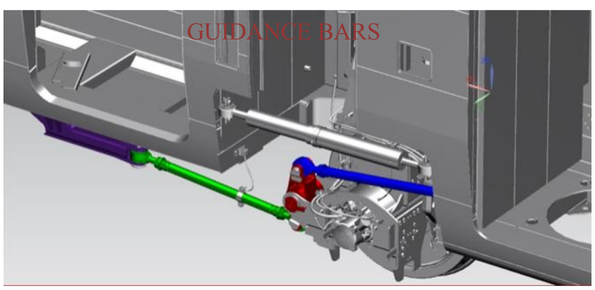


Figure 71 Guidance bars

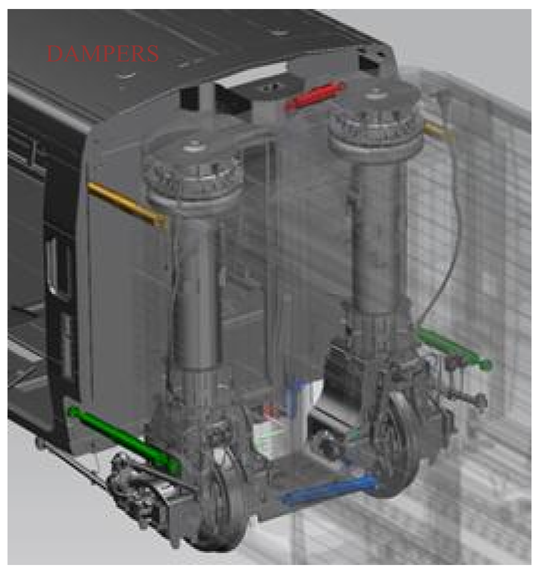


Figure 72 Dampers

There are two relevant failure modes, both of which occur only under extremely exceptional circumstances. They are discussed in 2.4.11.1 and 2.4.11.2.

2.4.11.1 Loss of vertical support

As explained in 2.4.3, the weight bearer bar system is a very safe system as it is both redundant and over designed. That section demonstrates that, assuming for some reason one weight bearer bar has failed, the remaining bar and structure can carry the entire weight of the suspended end of the car with a safety factor greater than 9. The above notwithstanding, let us assume the very unlikely event in which both weight bearer bars have failed. In this case, ignoring the contribution of the external steel box and internal elements (a conservative hypothesis) the entire vertical load (16,500 lbs.) will be supported by the coupler pin. The diameter of the weakest section is 1.551in., and the material is EN

10083-3 34CrMo4+QT steel with an ultimate strength of 116 kpsi. (Figure 73)

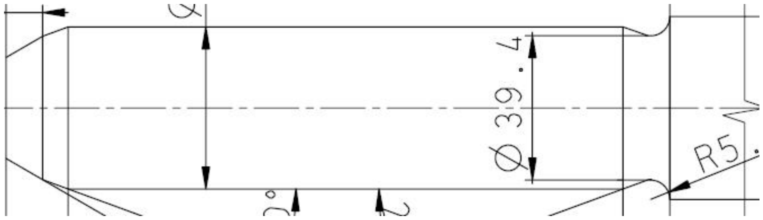


Figure 73 Coupler pin (dimensions in mm)

$$F_{lc} = \frac{n \cdot 0.5 \cdot \sigma \cdot A}{\gamma}$$

Where:

n: number of sections (n=1)

σ: ultimate strength (116 kpsi)

A: area

γ: stress concentration factor (γ=1.7)

Using these values the ultimate value in shear is 64,335 lbs. With this load the safety factor is 3.9 (64,335/16,500).

$$SF = \frac{F_{lc}}{P}$$

Where:

F_{lc}: ultimate value in shear (64,335 lbs., calculated above)

P: Weight at the suspended end (16,500 lbs.; see Figure 42)

It should be noted that the rotation about the articulated joint will be limited by rubber stops between cars and between the cars and the truck.

2.4.11.2 Lateral displacement.

During the accident investigation Talgo studied the statement in the grandfathering findings, which claims that the articulated cars will have a larger lateral displacement under unfavorable circumstances. Talgo does not agree with this statement as several connections must be broken to detach two cars and allow free lateral movement. Further support comes from engineering principles and behavior in actual accidents:

Engineering Principles:

Conventional passenger cars couple to each other by means of Type H[11] (“Tightlock”) couplers.

[11] While the focus in this accident is on performance in buff, it should be noted that the couplers used in conventional passenger trains have limited capacity in draft as well. The knuckle of a Type H coupler is designed to be the weak link and to fail in draft at 600,000 pounds force (APTA PR-M-RP-003-98 §7.4.4 Static tension test requirement)

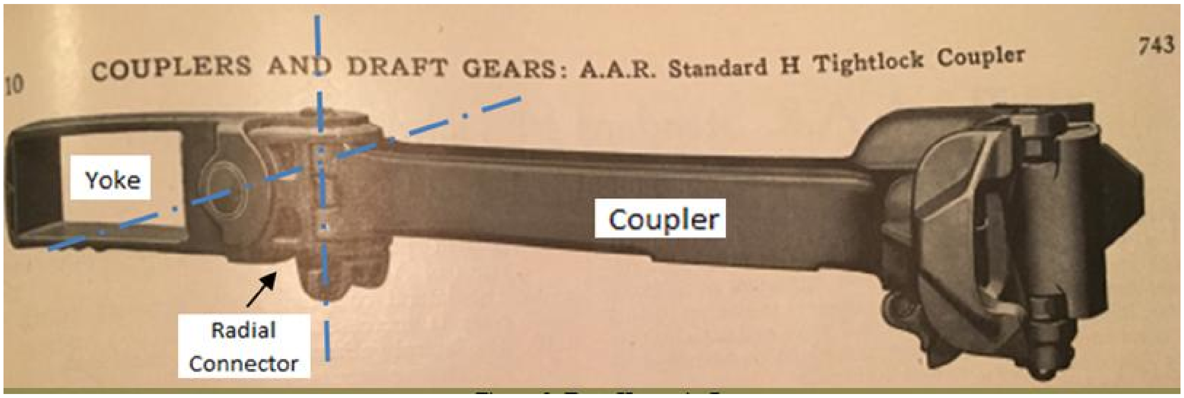


Figure 74 Type H coupler

A "Radial Connector" (shown below) connects this coupler to its yoke (which houses the draft gear that interfaces with the draft and buff lugs in the car frame).

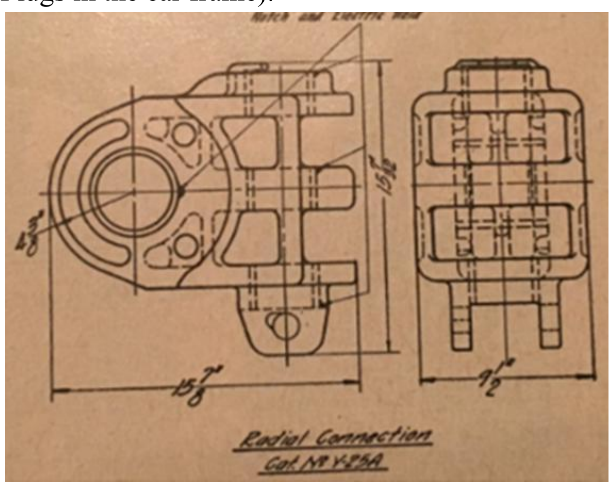


Figure 75 Radial connector

The coupler is thus completely free to rotate (within limits) about both a vertical and a horizontal axis (indicated by the blue center lines added in Figure 74. The vertical travel is limited to just a few inches by the coupler carrier, but lateral travel is about 12 inches each side of center (at the carrier), to permit the cars to enter and leave high degree curves.

As a result, conventional passenger trains are highly unstable in buff. This concern has not gone unnoticed. In fact, the AAR and APTA are currently in discussions because the Class Is are no longer willing to handle passenger locomotives with Type F couplers (which have a vertical axis pin like the Type H) rather than the "Alignment Control" couplers that are becoming universal on road freight locomotives. The freight roads understand that under heavy dynamic (locomotive) braking any lateral force, no matter how small, will rapidly feed back on itself and force the unstable passenger locomotive coupler to one side or the other. The misaligned coupler will then produce a lateral force component proportional to the buff force, easily rolling the rail and causing a derailment.

The same physics are present in a passenger consist. Because it is much lighter the buff loads are much less and the lateral component is negligible under normal service conditions. Of course, those forces are much higher in a collision, and the lateral force is frequently high enough to become a

contributing factor in, if not the primary cause of, the subsequent derailment.

The buckling can be lateral or vertical. An example of the former (Bourbonnais, Illinois) can be found in Section 3.1. An example of the latter is provided by the train-to-train collision in Beverly, Massachusetts, shown in Figure 76. In this collision the couplers mated, but then functioned like a pole vaulter's pole.

Figure 76 Beverly, MA, August 11, 1981

2.5 SPECIFIC PERFORMANCE OF C3 7504 AND C4 7424

This section describes the behavior of C3 7504 and C4 7424, which suffered the most severe damage. This analysis demonstrates that the derailment sequence described in Section 1.2 is consistent with the damage observed during the investigation. Again, our analysis of the accident indicates that the damage is understandable given the severity of the accident and does not indicate that the equipment performed poorly.

2.5.1 *Accessible Coach C3 7504*

The derailment sequence is described extensively in Section 1.2, but can be summarized as follows:

- The first five cars (power car 7903 through bistro 7303) caused C3 7504 to decelerate.
- C4 7424 and the cars behind it, still on the track, kept pushing C3 7504.
- With the front cars (following the locomotive) applying retarding force and the inertia of the rear cars, (still on the track) pushing, car C3 7504 started to rotate, breaking all the attachments between it and the adjacent cars and their shared trucks. (Figure 77 and Figure 78)

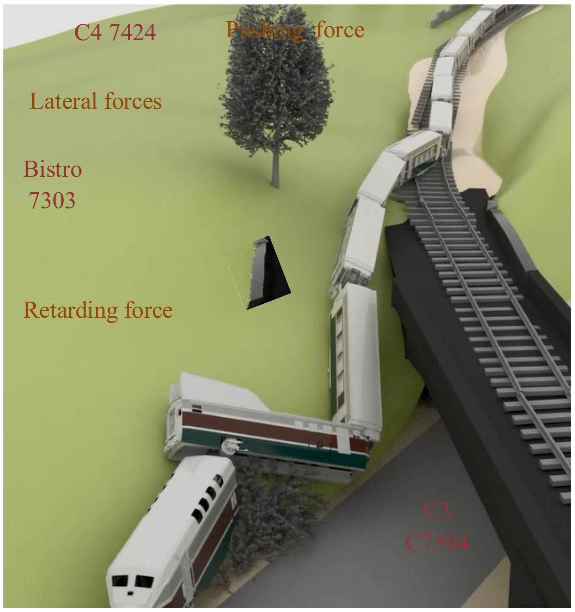


Figure 77 C3 7504. Prior to rotation

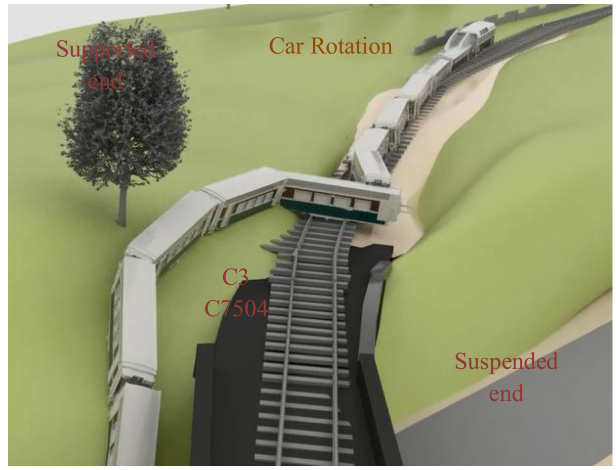


Figure 78 C3 7504. Rotating

- At this time, due to this rotation the car was moving sideways, hitting the concrete wall on its left side.

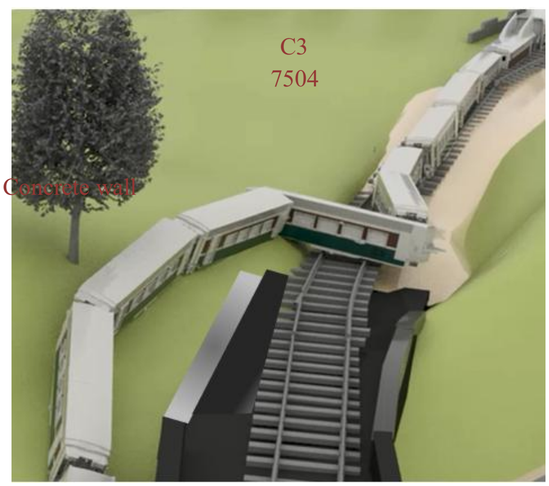


Figure 79 C3 7504. Moment prior to impact

- After the impact against the concrete wall, C3 7504 came to rest on top of C2 7554 and dining car 7804. The truck that belonged to C6 7422, three cars to the rear, was found under and next to C3. Part of the concrete wall was also found there. (Figures 80 and 81)

Figure 80 C3 7504. Final position

Figure 81 C3 7504. On site view

As can be clearly seen in Figure 82 through 85, the damage to C3 7504 was produced by an impact with a large rigid body at high speed. The damage was extensive and clearly the result of the collision with the overpass retaining wall.

Figure 82 C3 C7504 damage, left side

Figure 83 C3 C7504 damage, supported end

Figure 84 C3 C7504 damage, left side, detail (1)

Figure 85 C3 C7504 damage, left side, detail (2)

2.5.2 *Coach C4 7424*[12]

Following the same sequence described in 1.2, C4 7424 also was subject to lateral forces, breaking its connections with the adjacent cars and the shared trucks. At this point the car slid over the track and collided with the overpass, severely damaging the right side (Figure 89). After this collision, the car fell, rolling to its left, onto the highway and landing its roof. At that point the tractor-semi-trailer combination vehicle impacted it on its right side. The car came to rest under the bridge after rotating and sliding due to its own inertia and the collision with the truck.

Figure 86 C4 7424. Initial impact position

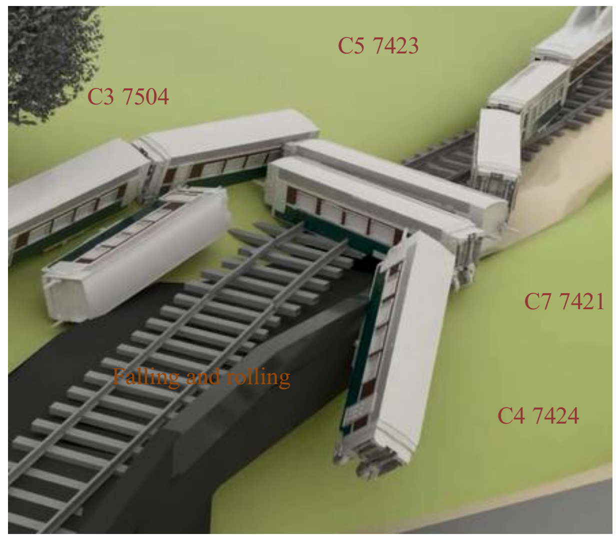


Figure 87 C4 7424. Falling from overpass

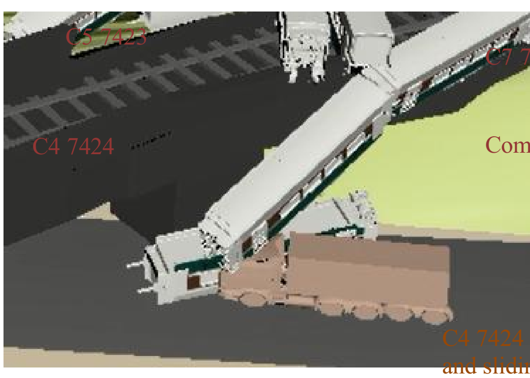


Figure 88 C4 7424. Collision with combination vehicle

Figure 89 C4 7424. Right side damage

[12] A note on figures 86 & 87:The simulation shows C3 7504 as rotating in a clockwise direction when viewed from the right side of the picture. In fact it rotated in the opposite direction, ending up with the bottom of the car towards the track and the top resting on the cars below

Figure 90 C4 7424. Left side damage

If the C4 had slid along the embankment, there would have been damage to the surrounding infrastructure, but no damage was evident on the guard rail or street light (yellow circles in Figure 91). Thus the marks on the embankment visible in the pictures below were likely there before the accident, requiring rejection of this hypothesis.

Figure 91 C4 7424. Hypothetical path of derailment (1)

Figure 92 C4 7424. Hypothetical path of derailment (2)

Figure 93 C4 7424. Hypothetical path of derailment (3)

Based on the above Talgo believes the probable path of derailment of C4 was a fall from the overpass approach fill instead of a slide along the embankment. Car inspection showed that the right tower support (Figure 94) was extensively deformed, damage consistent with a vertical impact with the highway.

Figure 94 C4 7424 Deformation due to vertical impact

2.6 RELEVANT LOCOMOTIVE DAMAGE

According to accident sequence the locomotive did not suffer a heavy lateral impact, but some components such as roof hatches were detached from it. These components, as others involved in the collision, are potentially dangerous to the train crew, nearby drivers or even passengers on the train, all of whom could be hit by these hatches. They have not been addresses in any report we have seen to date.

Figure 95 Overall view. Locomotive

Figure 96 Roof hatches located near passenger cars

3 OVERVIEW OF RECENT ACCIDENTS

3.1 RELEVANT U.S. ACCIDENTS

This section covers four examples of accidents with similarities to aspects of the DuPont accident (but less severe in some respects) in which conventional North American equipment produced failures similar to (but often worse than) those seen at DuPont. These examples show cars with their body structure completely destroyed, several trucks detached, broken couplers and large lateral displacements. They show that all of these problems are common to all equipment regardless of manufacturer. In several cases the consequences were worse even though the conditions were not as severe.

3.1.1 *Bourbonnais, Illinois, March 15, 1999*

https://www.ntsb.gov/investigations/accidentreports/pages/RAR0201.aspx
https://www.ntsb.gov/investigations/AccidentReports/Reports/RAR0201.pdf

This road crossing collision (with a combination tractor-semitrailer) provides a good example of lateral buckling. (It is a good example but by no means the only one, as similar results are apparent in many passenger train collisions.) All the passenger cars involved were Amtrak Superliners built to the current standards (even though some were not yet FRA requirements at the time they were built). In this accident the major pileup was at the front and all eleven fatalities were in the third car from the head end, so the chaos there attracted the most attention. That part of the train is shown in the photo to the left in Figure 97 below.

Figure 97 Bourbonnais

The instability problem is, however, illustrated by the rear four cars, which experienced a much lower deceleration rate than did those ahead of them but still derailed. That part of the train can be seen in the photo to the right in the above figure. It is quite clear that the buff forces produced by the deceleration of the train resulted in lateral components that caused lateral displacement. At least one car

fouled the adjacent main track. This collision occurred on (about the middle of an almost seven mile segment of) tangent track; there should have been no lateral forces at all. The positive feedback of the pinned connections of the Type H couplers magnified miniscule lateral components of the large buff forces, resulting in large enough ones to produce significant lateral displacement.

3.1.2 *Bronx, New York, December 1, 2013*

https://www.ntsb.gov/investigations/AccidentReports/Reports/RAB1412.pdf
https://www.ntsb.gov/investigations/AccidentReports/Reports/Metro-North_Bronx%202013_PreliminaryReport.pdf
https://www.mceldrewyoung.com/metro-north-train-derails-bronx-60-injured-4-people-killed-accident/

At the time of this accident the train was running at 82 mph in a 30 mph restriction. The situation was very similar to that at DuPont, but the speed ratio (82/30) was slightly (5%) higher (78/30). The cause of the over speed was inattention by the engineer. In this case the train broke into five parts. (The four failed connections are indicated by the red circles in Figure 98. At least one truck was detached, as can be seen in Figure 99 below.

One derailed car fouled an adjacent main track, two cars totally overturned and one car partially overturned. That very large lateral displacement occurred is clearly shown in the pictures. A secondary impact was avoided only because of the absence of additional track structures and trains.

In this accident four passengers were killed and 61 injured. All four fatalities were completely or partially ejected, and two of the seriously injured received their injuries due to contact with the ground when the cars were sliding along the ballast on their sides. Windows designed for removal by emergency responder are particularly subject to removal by ballast in this situation. There is clearly a trade-off here that should be evaluated.

Figure 98 Overall view, Bronx

Figure 99 Detached truck, Bronx

3.1.3 *Frankford Junction, Pennsylvania, May 12, 2015*

https://www.ntsb.gov/investigations/accidentreports/pages/RAR1602.aspx
https://www.ntsb.gov/investigations/AccidentReports/Reports/RAR1602.pdf

At the point of derailment this train was running at 106 mph in a 50 mph restriction, about twice the MAS.

In this case at least four connections between cars were broken, two cars turned over and one car was completely destroyed as can be seen in Figure 100 and 101. In the accident reports mechanical performance and technology are not cited as factors in the accident even though at least four trucks detached and the couplers failed at four or more locations (yellow circles in Figure 100) allowing the cars to overturn. As shown in that figure one of the overturned cars fell onto a main track a considerable distance from the one on which the derailment occurred, the very fear voiced by the FRA findings in the Talgo grandfathering report. That no secondary collision resulted was due only to the absence of additional track structures and other trains. At least five detached trucks are clearly visible in Figure 100 (red circles).

In this accident eight passengers were killed and 185 transported to hospitals.

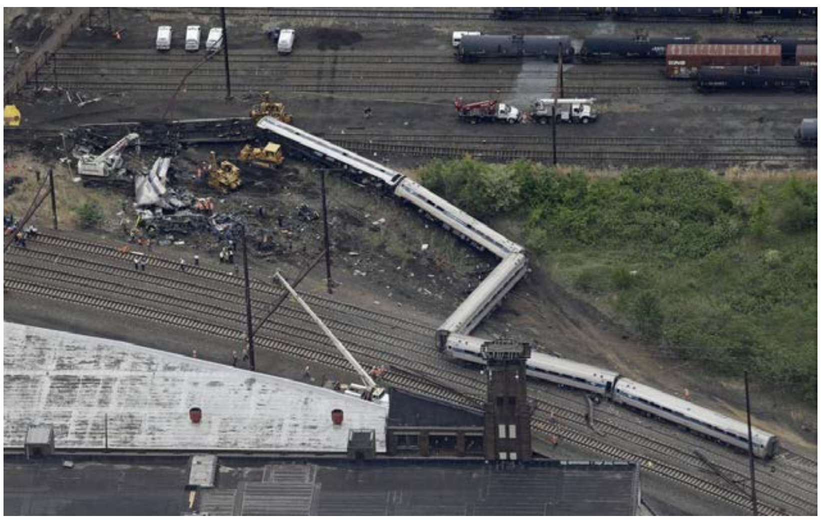


Figure 100 Overall view (1) Frankford

Figure 101 Overall view (2) Frankford

There are several similarities between this accident and DuPont. In both, Positive Train Control had not yet been implemented, there was a significant speed restriction in the middle of a relatively high speed segment and the engineers were not aware of their actual location with respect to the restrictions.

It is interesting to note that while both accidents were caused by over-speed in a curve, the ratio between the actual speed and that of the restriction at Frankford (106/50) was much below that at DuPont (78/30).

3.1.4 *Northfield, Vermont, October 5, 2015*

https://www.ntsb.gov/investigations/accidentreports/pages/rab1703.aspx
https://www.ntsb.gov/investigations/AccidentReports/Reports/RAB1703.PDF

At the time of this accident the train was running at its MAS of 59 mph. The derailment was caused by a large rock slide. The locomotive and four coaches derailed. The locomotive and the first car slid down a steep embankment. In this incident at least two couplers were broken, causing a large lateral displacement of the decoupled cars. Those cars did not foul an adjacent track only because there was none. As can be seen in Figure 102, at least one truck detached. The failed connections between cars are also clearly visible.

Figure 102 Overall view (1) Northfield

Figure 103 Overall view (2) Northfield

In this accident four train crew members and three passengers were injured.

3.2 RECENT TALGO INCIDENTS

3.2.1 *Chambers Bay, Washington, July 3, 2017*

In this accident, the *Mount Jefferson*, a Talgo Series 8[13] trainset, was running as Amtrak train 506, Portland to Seattle, with 267 passengers and five crew members on board. It was running at more than 40 mph when it hit an open derail protecting a moveable bridge, derailing the locomotive.

The locomotive turned onto its right side and may have gone into the water but the Talgo train configuration resulted in the entire trainset working together to keep it from rolling more than it did.

[13] The newer Series 8 is fully compliant with all current FRA regulations; however, it shares much of its design with the Series VI, including the method employed to prevent overturning.

Figure 104: Overall view

Figure 105: Track detail 2

Figure 106: View from behind

Figure 107: Locomotive supported by the train

This incident conclusively demonstrates the overturning resistance of Talgo equipment that was explained in 2.2.6

3.2.2 *Brazatortas, Ciudad Real (Spain), May 2017*

This incident involved a very high speed (Series S112) train set. One wheel of this train impacted a broken rail in a swing nose frog causing the derailment of that axle at 167 mph. The train stopped 1.614 miles [2598 m] from the point of derailment, with the entire trainset on the track except for the one derailed truck. The final investigation showed that the cause of the incident was the broken rail. No injuries and only minor material damage resulted; no plastic deformation on truck frames or tower supports were found.

Both independent and Talgo experts agreed that this incident would likely have been catastrophic if conventional equipment had been involved.

The behavior in this incident supports the position that Talgo rolling stock presents a high resistance to rollover events as the preceding and following cars prevent the derailment of axles.

Figure 108 Track detail (1)

Figure 109 Track detail (2)

Figure 110 Damaged left wheel, rolling assembly car 6

Figure 111 Damaged left wheel, rolling assembly car 7

This example demonstrates the stability of Talgo equipment even under very unfavorable conditions. It keeps the train on track even when an axle is derailed.

4 SUMMARY AND CONCLUSION

4.1 FINDINGS

1. The derailed trainset was properly maintained, per the Original Equipment Manufacturer Maintenance Plan and Manual.
2. On site car inspections demonstrates there were no permanent deformation on the frame of car body structure due to compressive forces.
3. No evidence of climbing was detected in the post-accident investigation. The weight bearer bar system worked properly.
4. The evaluation of the behavior of the car body structure in car to car interactions, impacts against trucks and rollover events was good.
   The car body structure of the Talgo Series VI absorbed a large amount of energy. The deformation of the aluminum structures protected passengers from suffering higher accelerations compared to the rigid structures typical of North American equipment. These accelerations would almost certainly have cause significantly worse injuries to the passengers.
5. The presence of the overpass approach fill retaining walls and the difference in height between the track and the wooded area caused more severe damage to C3 7504.
6. Truck detachment is not unusual in very high energy accidents, regardless the type of truck or car. There is evidence that trucks are often detached in accidents involving conventional North American equipment. (See the pictures in Section 3.1.) The loads involved in this accident were higher than those considered in the truck attachment design or the FRA requirements for it. This conclusion is based on the truck attachment calculations made during project development and reviews in post-accident investigation in conjunction with the Crashworthiness group.
7. Separation of cars is also common in high energy train accidents. Section 3.1 of this report shows several cases where the cars equipped with traditional AAR couplers disconnected and produced large lateral displacements.
8. Post-accident investigation found no defects in the seat rotation locking mechanisms on the *Mt Adams*.
9. The emergency windows were found to have functioned as designed, allowing evacuation. No fatalities were caused by any loss of side glazing or inability to remove it after the accident.

4.2 PROBABLE CAUSE

Talgo concludes that the probable cause of the accident December 18, 2017, involving Amtrak train No. 501 consisting of the Talgo *Mt. Adams*, was an over speed at the curve located at MP 19.8.

The distance from the advance speed board to the curve, about two miles, is adequate to slow the train from 79 mph (the maximum authorized speed) to 30 mph (the speed restriction in the curve). The train engineer apparently did not notice this sign or the one at the curve until it was too late to slow the train. The accident occurred during the first revenue trip on this route, which suggests the engineer may not have been sufficiently familiar with it.

4.3 CONCLUSION

We believe it is clear that the behavior of the Talgo equipment was far better than what would have been expected of conventional equipment in similar circumstances. The distributed energy absorption of the Talgo equipment combined its light weight (which reduces the amount of kinetic energy that must be absorbed to bring the train to a stop) reduces the acceleration experienced by passengers and crew (and thus "secondary impact velocity" injuries). As demonstrated by the first group of cars at DuPont, the high degree of stability of Talgo equipment under heavy buff loading is much more likely to keep the equipment connected, upright and in line.

5 ENHACEMENTS AND RECOMMENDATIONS

It is clear that the Series VI equipment is safe as-is and can continue to be operated by any US rail operator with confidence. This accident tested the equipment under severe and extreme conditions for which no equipment is designed, either in the US or anywhere else. However, it does provide insight into ways to make its designs ever safer, and Talgo is always interested in such improvements. As result of this investigation, Talgo proposes the following enhancements to the Talgo Series VI.

5.1 WINDOW REMOVAL INSTRUCTIONS

The emergency windows of several cars were used for egress after the derailment, but several passengers and first responders reported that the instructions were confusing. On the exterior, under each side window there is a sign which indicates the proper way to use the window in case of emergency. Currently the non-emergency windows are marked at the bottom with the text *"EMERGENCY Talgo Window removal. All windows are breakable using a sharp, heavy object"*. Emergency windows have two different pictograms at the bottom: *"Emergency exit"* and *"Emergency instructions"*. Talgo propose to change the pictograms as follows:

1. The pictograms should be placed at the quarter points as shown in 3. (Currently the pictograms for emergency windows are located at the ends of the windows as shown in Figure 112.)

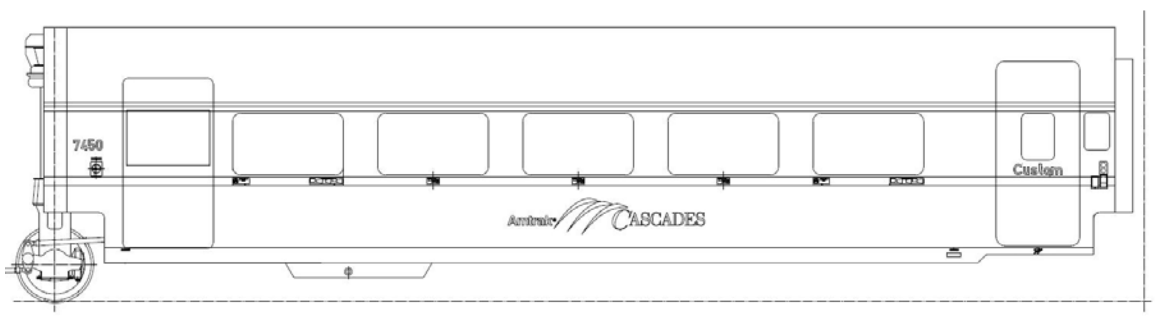


Figure 112 Current location of instruction signage

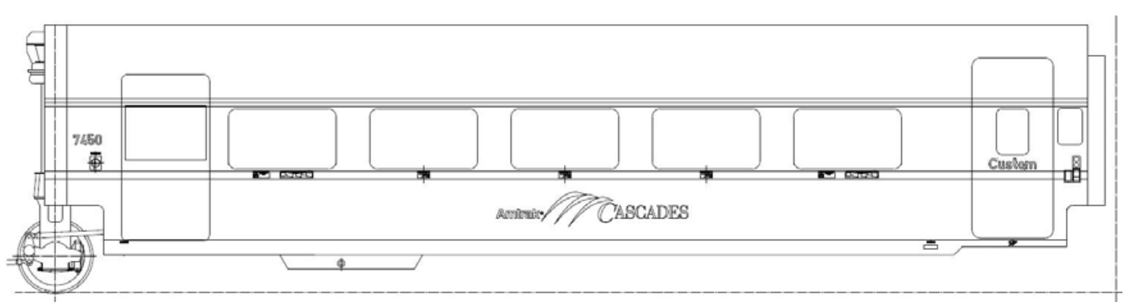


Figure 113 Proposed signage locations

2. Each text should refer only to one window. The text should indicate "*EMERGENCY. This window is breakable using a sharp, heavy object"*.
   The pictograms for emergency windows should not be changed.

5.2 TRUCK TO CAR BODY ATTACHMENT

After the *Mt. Adams* derailment at DuPont, Amtrak and Talgo met and decided to explore how to increase the attachment strength between rolling assemblies and car bodies (going above and beyond the regulation). After researching various options, Talgo confirms that it can install additional attachments. These redundant attachments between the rolling assembly and car body will increase the retention strength by another 250 kip. The total would thus be 500 kip, double the FRA requirement.

In the illustration below (Figure 114), blue attachments represent the existing ones and red indicates the new ones being proposed.

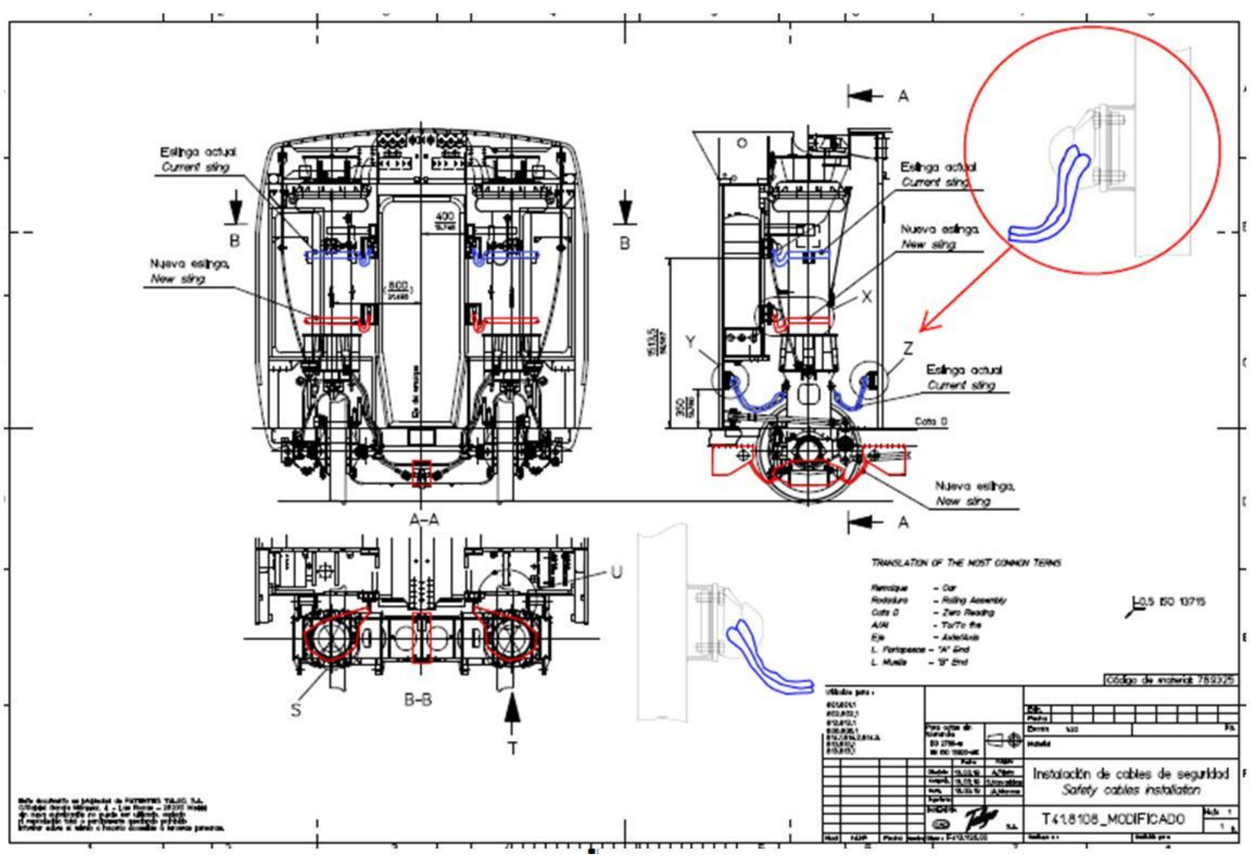


Figure 114 Proposed enhancements for rolling assembly attachment

5.3 WHEELCHAIR LIFT ATTACHMENT

In the DuPont accident an apparent combination of forces cause two lifts to disengage from their attachments. As per Amtrak request, in order to increase the attachment strength between the wheelchair lift and the car body, Talgo researched options and can confirm that additional attachments can be installed. Depicted below are two examples. These designs would act as redundant safety.

Figure 115 Proposed enhancements for wheelchair lift attachment (Option A)

Figure 116 Proposed enhancements for wheelchair lift attachment (Option B)